

Scotland's Rural College

Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: evidence from long-term experiments with wheat-maize cropping systems in China

Zhang, X; Sun, N; Wu, L; Xu, M; Bingham, IJ; Li, Z

Published in:
Science of the Total Environment

DOI:
[10.1016/j.scitotenv.2016.03.193](https://doi.org/10.1016/j.scitotenv.2016.03.193)

First published: 18/04/2016

Document Version
Peer reviewed version

[Link to publication](#)

Citation for pulished version (APA):

Zhang, X., Sun, N., Wu, L., Xu, M., Bingham, IJ., & Li, Z. (2016). Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: evidence from long-term experiments with wheat-maize cropping systems in China. *Science of the Total Environment*, 562, 247 - 259. <https://doi.org/10.1016/j.scitotenv.2016.03.193>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Manuscript Number: STOTEN-D-16-00432R1

Title: Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: evidence from long-term experiments with wheat-maize cropping systems in China

Article Type: Research Paper

Keywords: Soil organic carbon; yield; yield stability; manure application; straw return; China

Corresponding Author: Prof. Minggang XU, Ph D

Corresponding Author's Institution: Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences

First Author: Xubo Zhang, Ph.D

Order of Authors: Xubo Zhang, Ph.D; Nan Sun; Lianhai Wu, Ph.D; Minggang XU, Ph D; Ian J Bingham J Bingham, Ph.D; Zhongfang Li

Abstract: Although organic carbon sequestration in agricultural soils has been recommended as a 'win-win strategy' for mitigating climate change and ensuring food security, great uncertainty still remains in identifying the relationships between soil organic carbon (SOC) sequestration and crop productivity. Using data from 17 long-term experiments in China we determined the effects of fertilization strategies on SOC stocks at 0-20 cm depth in the North, North East, North West and South. The impacts of changes in topsoil SOC stocks on the yield and yield stability of winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) were determined. Results showed that application of inorganic fertilizers (NPK) plus animal manure over 20-30 years significantly increased SOC stocks to 20-cm depth by 32-87% whilst NPK plus wheat/maize straw application increased it by 26-38% compared to controls. The efficiency of SOC sequestration differed between regions with 7.4-13.1% of annual C input into the topsoil being retained as SOC over the study periods. In the northern regions, application of manure had little additional effect on yield compared to NPK over a wide range of topsoil SOC stocks (18 - >50 Mg C ha⁻¹). In the South, average yield from manure applied treatments was 2.5 times greater than that from NPK treatments. Moreover, the yield with NPK plus manure increased until SOC stocks (20-cm depth) increased to ~35 Mg C ha⁻¹. In the northern regions, yield stability was not increased by application of NPK plus manure compared to NPK, whereas in the South there was a significant improvement. We conclude that manure application and straw incorporation could potentially lead to SOC sequestration in topsoil in China, but beneficial effects of this increase in SOC stocks to 20-cm depth on crop yield and yield stability may only be achieved in the South.

Response to Reviewers: Response to reviewers' comments

We are grateful to the reviewers for their assessment of the manuscript. Please see below our response to their comments.

Reviewers/Editor comments:

Reviewer #1:

The study seems interesting. However, I don't like the use of word "threshold" in the paper as it sounds like SOC content beyond the threshold would produce negative impacts on yield and C sequestration, which is not consistent to the intention of the paper. Maybe it can be referred as the maximal yield-responsive SOC content. In addition, the use of SOC threshold for C sequestration is not appropriate because the higher SOC the better for climate mitigation, and there is no such issue as threshold SOC.

Authors' response

Many thanks for your suggestion. The word 'threshold' has been changed to 'maximal yield-responsive SOC stock' throughout the text.

Reviewer #2:

Be more critical to your data. I attached an annotated ms with many comments.

Authors' response

Many thanks for the constructive comments of the manuscript. Firstly, we have revised all the suggestion and correction on phrase following your comments (blue color in your annotated version), and secondly responded the comments or marked questions (yellow color in your annotated version) below:

Research highlights were changed to:

- 7.4–13.1% of total C input over 20–30 years was accumulated as soil organic C in the top 20 cm of soil
- SOC had relatively little impact on crop yield and its stability in northern China
- SOC significantly improved crop yield and its stability in southern China
- In southern China yield and yield stability increased with SOC stocks up to a maximum stock value of ~35 Mg C ha⁻¹

Title

Thanks for the comments. Title has been revised as 'Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: evidence from long-term experiments with wheat-maize cropping systems in China'.

Abstract

Line 21: 'carbon' has been changed to 'organic carbon'.

Line 23: 'carbon' has been changed to 'soil organic carbon (SOC)'.

Line 29: 'manure' has been changed to 'animal manure'.

Line 30: 'approximately two decades' has been changed to 'over 20 to 30 years'

Line 30: 'storage' has been changed to 'stocks to 20-cm depth'

Line 31: 'straw' has been changed to 'wheat and maize straw'

Line 36: 't' has been revised as 'Mg' throughout the MS.

Line 38: 'optimum' has been deleted.

Line 39: 'DW' has been deleted. It means SOC content (%).

Line 44: 'SOC increase' has been changed to 'increase in SOC stocks to 20-cm depth'

Introduction

Line 50:

Comments: "the magnitude of yield increases by SOC-induced improvement in soil quality depends on soil type, crop, management, antecedent SOC concentration, and the weather during the growing season (Lal 2014)"

Authors' response

We acknowledge this point, but feel that to incorporate would break the flow of the rest of the paragraph. Citing Lal 2014 will direct a reader to this.

Line 51: 'Yu et al., 2006' has been deleted.

Line 52: 'Zhang et al., 2013' has been deleted.

Line 52: 'providing various ecosystem services' has been changed to 'providing various ecosystem services, such as soil water retention, etc.'

Line 57:

Comments: Speculative, even IPCC did not consider SOC sequestration until recently and only with the announcement of the 4 per 1000 initiative at COP21 in Paris in December 2015 some momentum was generated

Authors' response: Thanks for the comments. We realized that IPCC only announced the 4 per 1000 initiative at COP21 in Paris in December 2015, however, there are more than 30,000 papers relevant with soil carbon sequestration. Thus, it means people have been paid attention to carbon sequestration.

:

Line 58: 'sequestering carbon (C)' has been changed to 'sequestering organic carbon'.

Line 60: Soil depth has been added '1% increase of SOC content in topsoil (0-20 cm)'.

Line 68: 'maintained' has been changed to 'increased'

Line 69: Reference '(Fan et al., 2010)' has been added.

Line 75:

Comments: But sufficient to support crop production in China? Or is this only possible by large fertilizer inputs?

Authors' response: In the past, crop production increase in China mainly depended on large chemical fertilizer input.

Line 84: Soil depth has been added as 'SOC in the topsoil (0-20 cm)'.

Line 90-92: we have revised the sentence as 'It is challenging to quantify the contribution of SOC to either maintaining or stabilizing crop yield, as the contribution could be concealed by other factors given the complex interactions that occur between soil, root systems and canopies (Bingham, 2001). Most studies conducted across the world have suggested that there is some linear relationship between SOC stocks in the root zone and crop yield and its stability (Bauer and Black, 1994; Beyer et al., 1999; Lal, 2010; Smith, 2004).'

Line 89: 'maintaining and stabilizing' has been changed to 'either maintaining or stabilizing'.

Line 97: 'SOC' has been changed to 'SOC stocks in the root zone'.

Line 99: 'in the topsoil' has been added after 'SOC content'.

Methods and materials

Line 139:

Comments: Does this mean that 'N/A' in Table S1 stands for '0, 0'?

Authors' response: 'N/A' in table S1 mean '0, 0', we have been added this in table S1.

Line 142:

Comments: Add information on tillage frequency and tillage depth
Authors' response: The information on tillage frequency and tillage depth have been added in table

Line 153:

Comments: Were P and K application rates similar at the sites? Data on application rates?

Authors' response: The information of P and K fertilizers has been added in table 1.

Line 168: Soil depth has been added as 'incorporated into the soil (0-20 cm depth) immediately after harvest.'

Line 178:

Comments: Does this mean that plots were implemented on slopes? If yes, add degrees of slopes

Authors' response: No, there are no slopes in the plots. The boundaries were built to avoid lateral exchange of water and nutrients between adjacent plots by possible hydrops after heavy rainfall.

Line 188: Device for collecting soil samples has been added.

Line 199: Measurement of soil bulk density has been added to the materials and methods

Line 211: Soil depth has been added.

Line 227: SBD has been changed to BD

Line 226:

Comments: You must describe how bulk density was determined

Authors' response: The method for determining soil bulk density has been added in Line 199.

Line 240: 'Relative yield' has been changed to 'Crop relative yield'.

Line 266:

Comments: I do not understand this, SOC varies from year to year and so does yield - why should yield vary of the period with the average SOC in the period?

Authors' response:

SOC changes only gradually over time, whilst yield variations can be large. Plotting one against the other allows some understanding as to the whether there are benefits of maintaining large SOC stocks to reduce annual variation in yield

Line 270: Details of β_0 , β_1 and β_2 has been added as 'where β_0 is the lower value of CV (lower value of asymptotic line), $\beta_0 + \beta_1$ is maximum value of CV and β_2 is the decrease rate of CV.'

Line 272: The information of P and K fertilizers has been added in table 1.

Results

Line 287 - 296: We have revised this paragraph following your comments.

In addition, the ratios of decrease or increase in yield trends are correct, because we have only considered significant trends as you suggested. The % values are the number of sites with significant positive or negative trends expressed as a % of the total number of sites.

Line 298:

Comments: Not different as those share the same letter

The sentence has been changed to 'The highest relative yields were in the manure applied treatments, followed by NPKS.'

Line 298-302

Comments: Statistical analyses in Table 3 were within treatments for each region - where is the statistical comparison between regions shown?

Authors' response: Many thanks for the comments. In the MS, we only compared the crop relative yield among the treatments but did not compare the relative yield among regions directly, because soil types and

fertility in the regions are different that may lead possible confusion for our results.

Line 317: The statistical significances have been added.

Line 323: The sentence has been revised as 'Moreover application of NP and NPK did not reduce this variability unlike the response in the northern regions.'

Line 324: 'were required' has been changed to 'Applications of manure (NPM, NPKM, hNPKM) reduced yield variability to values comparable to the other regions'

Line 325-327: The sentence 'Thus, wheat and maize grown with manure applications along with inorganic fertilizers showed greater resilience to climatic variability and other adverse conditions in the regions' has been deleted.

Line 329-345:

Comments: Unclear - there is no reason to believe that fertilizer additions had different effects on SOC stocks before and after 2000. Does this mean fertilizer was added only after 2000? You must explain this arbitrary division in Materials and Methods. As SOC stock changes occur slowly, a comparison of SOC stocks at the end with those at the beginning of the experiment would be appropriate.

Authors' response: We have rewritten the whole paragraph by comparing the SOC stocks in beginning and end of experiments.

Line 364-365:

Comments: As experimental periods differ, you must analyze the rates (Mg C ha⁻¹ yr⁻¹) and not per period - otherwise you cannot compare the regions.

Authors' response: We have redrawn the Figure 4 by analyzing the relationship between change rates of SOC stocks (Mg C ha⁻¹ yr⁻¹) and annual C inputs.

Line 368: 'efficiency of sequestration' has been changed to 'retention rate of C inputs'.

Line 371: 'were pooled' has been changed to 'were combined'.

Line 380: 'the SOC storage' has been changed to 'the average SOC stocks over experimental period'

Line 383: 'a significant exponential decrease' has been changed to 'an exponential decrease trend'.

Discussion

Line 387: the title of section 4.1 has been changed to 'Impact of fertilization management on topsoil SOC stocks'

Line 388: 'sequestered' has been changed to 'retained'

Line 391: 'fertilization regime' has been changed to 'N fertilizer'

Line 392: 'had a strong influence' has been changed to 'influenced the rate of C sequestration'

Line 395: 'balanced fertilization' has been changed to 'Balanced application of N, P, and K inorganic fertilizers'

Line 395: We have added discussion from line 395 to line 397.

Line 397: 'the average rates of change of SOC' has been changed to 'The annual change rates of SOC to 20-cm depth'

Line 401: 'at the 20-cm soil depth' has been added.

Line 398-399: 'Significant positive linear relationships were found between SOC increment and cumulative C input to the soils over the experimental period (Fig. 4)' has been deleted.

Line 405: 'slope of the relationship' has been revised as 'The slope of linear equation'.

Line 406: '...is retained (sequestered) in the soil (the sequestration efficiency)' has been changed to '...is retained in the soils'

Line 407: Yes, it means for each 1 Mg C ha⁻¹ more input, SOC stock to 20-cm increased by 0.07 - 0.16 Mg C ha⁻¹.

Line 407: the sentence 'The results suggest that differences between regions in the rate of SOC gain following the various fertilizer treatments were the result of differences in rate of SOC decomposition and thus retention and not just C inputs' has been deleted as it was speculative.

Line 410: 'sequestration efficiency' has been changed to 'retention rate of a site'

Line 410:

Comments: 'R²=0.48' Indicates poor explanation.

Authors' response: In this sentence, we presented that the initial SOC stocks do not related to its retention rate, thus we thought the poor 'R²' here is appropriate.

Line 410: Because there are no proper references, thus we have changed 'suggesting' to a possible reason as 'this may due to the differences in retention rate were largely the result of differences in climate or soil factors other than initial C content.'

Line 413-419: The sentence has been revised as 'The range of sequestration efficiencies was similar to that observed from the Indian humid subtropical plains at 20-cm depth under a rice-wheat over 20-30 years (7.6-14%, Majumder et al., 2008) and a rice-lentil (*Lens culinaris*) system (9.9%, Srinivasarao et al., 2012), but lower than that from the temperate region of North America (14-21%, Rasmussen and Collins, 1991) and higher than that from topsoil of subtropical regions under a rice-wheat-jute (*Corchorus olitorius* L.) system (4-5%, Majumder et al., 2007).'

Line 420: The first paragraph 'Soil organic matter is important in maintaining soil structure, porosity, water infiltration and retention, and can improve soil chemical buffering capacity, biological activity and nutrient cycling (Loveland and Webb, 2003; Johnston et al., 2009; D'Hose et al., 2014; Oelofse et al., 2015). Quantifying the effect of SOC storagestocks on crop yield has, therefore, become increasingly important in the context of ensuring food security (Lal 2004). Previous studies reported that SOC storagestocks was positively correlated with crop yield in a range of production environments (Bauer and Black, 1994; Rasmussen and Parton, 1994; Cotching et al., 2002; Farquharson et al., 2003; Pan et al., 2009; Yan and Gong, 2010). However, others have found no significant correlation between changes in SOC and crop yields (Beyer et al., 1999; Oelofse et al., 2015) or that the correlation depends on the type of farming system (organic versus conventional; Brock et al., 2011)'has been deleted.

Line 421: 'problematic' has been changed to 'difficult'.

Line 421-422: 'SOC' has been changed to 'SOC stocks'.

Line 424: 'also alter the supply of nutrients' has been revised as 'also alter the supply of nutrients alongside effects on soil structure and water holding capacity etc.'

Line 431: 'pooled' has been changed to 'combined'.

Line 432: 'an apparent threshold' has been changed to 'apparent maximal yield-responsive SOC stocks'.

Line 435-460: We have added some references and discussions.

Line 466: 'concentration' has been changed to 'concentrations (ranged from 0.5% to 1.9%)'.

Line 467: '2%' has been changed to '2% to 0-20 cm soil depth'.

Line 470: 'discussed above' has been changed to 'to the northern regions'

Line 477: A reference has been added.

Line 481: 'If this is the case then it is clear the same restrictions and dependency on SOC are not found in the more temperate northern regions' has been deleted.

Fig legends

Line 742: 'Long-term trials' has been changed to long-term experiments throughout the text.

Line 747: 'N/A' means that there was no NPS treatment in the North east, North and South region. We have added the description in the legend.

Line 760: We have redrawn the Figure 4 by analyzing the relationship between change rates of SOC stocks ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$) and annual C inputs.

Tables

We have revised all the suggestion and correction following your comments.

Table S1: The data (except climate data) were all collected from the experiments. In addition, we have added a note in the table 'Note: Climate data were collected from the China meteorological sharing service system (<http://cdc.cma.gov.cn/>)'

Table S2: The data were all collected from the experiments. And the units have been placed beneath the elements.

Table S3: 'N/A' has been changed to 'None'.

Reviewer #5: Manuscript no. STOTEN-D-16-00432

Soil carbon sequestration in agricultural soil is important in terms of productivity and improvement of fertilizer use efficiency. Though worldwide diverse results came in terms of productivity enhancement with respect to SOC sequestration. But it's importance is unquestionable. More and more studies are required for quantification of yield improvements and stability through improvement of root zone carbon in different crops/cropping systems throughout the world. Under this context, this study is relevant. But the study has more regional importance.

Authors' response

Many thanks for your constructive comments. We have revised the MS following the comments and responded the questions below:

Title:

Cropping system and Location (country name) can be included in the title to make it clearer. More emphasis in the paper was on effects of fertilization strategies on soil organic carbon storage- that may be emphasized in title itself.

Authors' response

Many thanks for your suggestion. The title has been revised as 'Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: evidence from long-term experiments with wheat-maize cropping systems in China'.

Introduction:

Recent findings should be included.

Introduction should also have the effects of fertilization strategies on soil organic carbon storage related research findings.

Authors' response

Many thanks for the comments. We have rewritten part of the introduction and added the review of fertilization strategies impact on SOC (Line 79-88). The references in year 2015 have been added in line 81.

Method and Material:

Data and statistical analysis- Crop Relative Yield for minimizing the influence of crop variety and climatic variation should be explained elaborately. It's not very clear.

Authors' response

Many thanks for the comments. We have been revised the description of relative crop yield in line 239-248.

Treatment details should be given. In chemical fertilizers: dose, time of application and source of application. In organic manure, how it was applied? what is the amount? Is it dry weight basis or wet weight basis etc.

Authors' response

Many thanks for the comments. The doses of chemical fertilizers (N, P and K) have been added in table 1. Time and source of application have been added in line 159-161. Organic manure was applied to surface of soils and it was wet weight basis.

Equation no. 4 (A and B parameters) and Equation no. 6 -Fitted parameters are not defined anywhere so replicating the work will not be possible.

Authors' response

Many thanks for the comments. We have added the description of parameters in equation 4 and 6 to line 252-253 and line 269-270.

Results and Discussion:

I am doubtful about the analysis of the result. Better to use PCA for this as yield depends on lot of variables mainly soil type and texture, pH etc.

Soil classification also shows wide difference between soil types eg. Regosols, Cambisols are developing soil with very less or no profile development (in south), in north calcareous Cambisols, in north east Sod organic-accumulative and in north west accumulation of organic matter, high base status soils. How these are compared? Probably by PCA we can get the real picture that how sequestered carbon affects crop productivity and stability.

Authors' response

Many thanks for the constructive comments of the manuscript. We have considered the principal component analysis to explain our results. However, the PCA only show us SOC stock is one of the most important factors on crop productivity which have been reviewed in the introduction section, but not how SOC stock impact on crop yield. In our MS, the main objective was to establish the relationships between SOC and relative yield and yield stability and to determine whether these differed between regions. Thus, we did not use the PCA in the MS.

Why relative yield is increased in south than in north? It is not clearly discussed.

Authors' response

Thanks for the comments. We have re-discussed in line 468-477.

In North east SOC storage is more but yield is less why?

Authors' response

Thanks for the comments. Firstly, the 'yield' is the relative yield that actual yield of either wheat or maize from a treatment at a site in a year divided by yield in NPK at the site in the year. In the North east, the crop yield in the NPK treatment was not significant differed from the yield in the manure applied treatments, which not like that in the other regions that crop yield in the NPK treatment was lower than that in the manure applied treatments. Therefore, the relative yield is less in the North east than those in the other regions.

In Fig. 6 also north east is not showing any clear trend line for yield stability, discussion part is not clear.

Authors' response

Thanks for the constructive comments. We have re-discussed in line 503 to 523.

References:

Year 2014 (only one reference) and 2015 references may be included.

Authors' response

The references in year 2015 have been added in line 81, 441 and 456.

Minggang Xu, Professor
Institute of Agricultural Resources and Regional Planning
Chinese Academy of Agricultural Sciences, Beijing 100081, China
Tel: +86-10-82105636
Email: mgxu@caas.ac.cn
March 23th, 2016

Editor

Science of the Total Environment

Dear editor,

We would like to submit our revised manuscript (Ms. Ref. No.: **STOTEN-D-16-00432**, **"Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: evidence from long-term experiments with wheat-maize cropping systems in China"** for your consideration. And we appreciate very much the constructive comments from you and three anonymous reviewers. We have revised our manuscript following suggestions and submit it for your consideration. Enclosed is our response to the comments.

Yours sincerely

Minggang Xu

Response to reviewers' comments

We are grateful to the reviewers for their assessment of the manuscript. Please see below our response to their comments.

Reviewers/Editor comments:

Reviewer #1:

The study seems interesting. However, I don't like the use of word "threshold" in the paper as it sounds like SOC content beyond the threshold would produce negative impacts on yield and C sequestration, which is not consistent to the intention of the paper. Maybe it can be referred as the maximal yield-responsive SOC content. In addition, the use of SOC threshold for C sequestration is not appropriate because the higher SOC the better for climate mitigation, and there is no such issue as threshold SOC.

Authors' response

Many thanks for your suggestion. The word 'threshold' has been changed to 'maximal yield-responsive SOC stock' throughout the text.

Reviewer #2:

Be more critical to your data. I attached an annotated ms with many comments.

Authors' response

Many thanks for the constructive comments of the manuscript. Firstly, we have revised all the suggestion and correction on phrase following your comments (blue color in your annotated version), and secondly responded the comments or marked questions (yellow color in your annotated version) below:

Research highlights were changed to:

- 7.4-13.1% of total C input over 20-30 years was accumulated as soil organic C in the top 20 cm of soil
- SOC had relatively little impact on crop yield and its stability in northern China
- SOC significantly improved crop yield and its stability in southern China
- In southern China yield and yield stability increased with SOC stocks up to a maximum stock value of $\sim 35 \text{ Mg C ha}^{-1}$

Title

Thanks for the comments. Title has been revised as 'Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: evidence from long-term experiments with wheat-maize cropping systems in China'.

Abstract

Line 21: 'carbon' has been changed to 'organic carbon'.
 Line 23: 'carbon' has been changed to 'soil organic carbon (SOC)'.
 Line 29: 'manure' has been changed to 'animal manure'.
 Line 30: 'approximately two decades' has been changed to 'over 20 to 30 years'
 Line 30: 'storage' has been changed to 'stocks to 20-cm depth'
 Line 31: 'straw' has been changed to 'wheat and maize straw'
 Line 36: 't' has been revised as 'Mg' throughout the MS.
 Line 38: 'optimum' has been deleted.
 Line 39: 'DW' has been deleted. It means SOC content (%).
 Line 44: 'SOC increase' has been changed to 'increase in SOC stocks to 20-cm depth'

Introduction

Line 50:

Comments: "the magnitude of yield increases by SOC-induced improvement in soil quality depends on soil type, crop, management, antecedent SOC concentration, and the weather during the growing season (Lal 2014)"

Authors' response

We acknowledge this point, but feel that to incorporate would break the flow of the rest of the paragraph. Citing Lal 2014 will direct a reader to this.

Line 51: 'Yu et al., 2006' has been deleted.

Line 52: 'Zhang et al., 2013' has been deleted.

Line 52: 'providing various ecosystem services' has been changed to 'providing various ecosystem services, such as soil water retention, etc.'

Line 57:

Comments: Speculative, even IPCC did not consider SOC sequestration until recently and only with the announcement of the 4 per 1000 initiative at COP21 in Paris in December 2015 some momentum was generated

Authors' response: Thanks for the comments. We realized that IPCC only announced the 4 per 1000 initiative at COP21 in Paris in December 2015, however, there are more than 30,000 papers relevant with soil carbon sequestration. Thus, it means people have been paid attention to carbon sequestration.

:

Line 58: 'sequestering carbon (C)' has been changed to 'sequestering organic carbon'.

Line 60: Soil depth has been added '1% increase of SOC content in topsoil (0-20 cm)'.

Line 68: 'maintained' has been changed to 'increased'

Line 69: Reference '(Fan et al., 2010)' has been added.

Line 75:

Comments: But sufficient to support crop production in China? Or is this only possible by large fertilizer inputs?

Authors' response: In the past, crop production increase in China mainly depended on large chemical fertilizer input.

Line 84: Soil depth has been added as 'SOC in the topsoil (0-20 cm)'.

Line 90-92: we have revised the sentence as 'It is challenging to quantify the contribution of SOC to either maintaining or stabilizing crop yield, as the contribution could be concealed by other

factors given the complex interactions that occur between soil, root systems and canopies (Bingham, 2001). Most studies conducted across the world have suggested that there is some linear relationship between SOC stocks in the root zone and crop yield and its stability (Bauer and Black, 1994; Beyer et al., 1999; Lal, 2010; Smith, 2004).’

Line 89: ‘maintaining and stabilizing’ has been changed to ‘either maintaining or stabilizing’.

Line 97: ‘SOC’ has been changed to ‘SOC stocks in the root zone’.

Line 99: ‘in the topsoil’ has been added after ‘SOC content’.

Methods and materials

Line 139:

Comments: Does this mean that 'N/A' in Table S1 stands for '0, 0'?

Authors’ response: ‘N/A’ in table S1 mean ‘0, 0’, we have been added this in table S1.

Line 142:

Comments: Add information on tillage frequency and tillage depth

Authors’ response: The information on tillage frequency and tillage depth have been added in table

Line 153:

Comments: Were P and K application rates similar at the sites? Data on application rates?

Authors’ response: The information of P and K fertilizers has been added in table 1.

Line 168: Soil depth has been added as ‘incorporated into the soil (0-20 cm depth) immediately after harvest.’

Line 178:

Comments: Does this mean that plots were implemented on slopes? If yes, add degrees of slopes

Authors’ response: No, there are no slopes in the plots. The boundaries were built to avoid lateral exchange of water and nutrients between adjacent plots by possible hydrops after heavy rainfall.

Line 188: Device for collecting soil samples has been added.

Line 199: Measurement of soil bulk density has been added to the materials and methods

Line 211: Soil depth has been added.

Line 227: SBD has been changed to BD

Line 226:

Comments: You must describe how bulk density was determined

Authors’ response: The method for determining soil bulk density has been added in Line 199.

Line 240: ‘Relative yield’ has been changed to ‘Crop relative yield’.

Line 266:

Comments: I do not understand this, SOC varies from year to year and so does yield - why should yield vary of the period with the average SOC in the period?

Authors’ response:

SOC changes only gradually over time, whilst yield variations can be large. Plotting one against the other allows some understanding as to whether there are benefits of maintaining large SOC stocks to reduce annual variation in yield

Line 270: Details of β_0 , β_1 and β_2 has been added as ‘where β_0 is the lower value of CV (lower value of asymptotic line), $\beta_0 + \beta_1$ is maximum value of CV and β_2 is the decrease rate of CV.’

Line 272: The information of P and K fertilizers has been added in table 1.

Results

Line 287 – 296: We have revised this paragraph following your comments. In addition, the ratios of decrease or increase in yield trends are correct, because we have only considered significant trends as you suggested. The % values are the number of sites with significant positive or negative trends expressed as a % of the total number of sites.

Line 298:

Comments: Not different as those share the same letter

The sentence has been changed to ‘The highest relative yields were in the manure applied treatments, followed by NPKS.’

Line 298-302

Comments: Statistical analyses in Table 3 were within treatments for each region - where is the statistical comparison between regions shown?

Authors’ response: Many thanks for the comments. In the MS, we only compared the crop relative yield among the treatments but did not compare the relative yield among regions directly, because soil types and fertility in the regions are different that may lead possible confusion for our results.

Line 317: The statistical significances have been added.

Line 323: The sentence has been revised as ‘Moreover application of NP and NPK did not reduce this variability unlike the response in the northern regions.’

Line 324: ‘were required’ has been changed to ‘Applications of manure (NPM, NPKM, hNPKM) reduced yield variability to values comparable to the other regions’

Line 325-327: The sentence ‘Thus, wheat and maize grown with manure applications along with inorganic fertilizers showed greater resilience to climatic variability and other adverse conditions in the regions’ has been deleted.

Line 329-345:

Comments: Unclear - there is no reason to believe that fertilizer additions had different effects on SOC stocks before and after 2000. Does this mean fertilizer was added only after 2000? You must explain this arbitrary division in Materials and Methods. As SOC stock changes occur slowly, a comparison of SOC stocks at the end with those at the beginning of the experiment would be appropriate.

Authors’ response: We have rewritten the whole paragraph by comparing the SOC stocks in beginning and end of experiments.

Line 364-365:

Comments: As experimental periods differ, you must analyze the rates (Mg C ha⁻¹ yr⁻¹) and not per period - otherwise you cannot compare the regions.

Authors’ response: We have redrawn the Figure 4 by analyzing the relationship between change rates of SOC stocks (Mg C ha⁻¹ yr⁻¹) and annual C inputs.

Line 368: ‘efficiency of sequestration’ has been changed to ‘retention rate of C inputs’.

Line 371: ‘were pooled’ has been changed to ‘were combined’.

Line 380: ‘the SOC storage’ has been changed to ‘the average SOC stocks over experimental

period’

Line 383: ‘a significant exponential decrease’ has been changed to ‘an exponential decrease trend’.

Discussion

Line 387: the title of section 4.1 has been changed to ‘Impact of fertilization management on topsoil SOC stocks’

Line 388: ‘sequestered’ has been changed to ‘retained’

Line 391: ‘fertilization regime’ has been changed to ‘N fertilizer’

Line 392: ‘had a strong influence’ has been changed to ‘influenced the rate of C sequestration’

Line 395: ‘balanced fertilization’ has been changed to ‘Balanced application of N, P, and K inorganic fertilizers’

Line 395: We have added discussion from line 395 to line 397.

Line 397: ‘the average rates of change of SOC’ has been changed to ‘The annual change rates of SOC to 20-cm depth’

Line 401: ‘at the 20-cm soil depth’ has been added.

Line 398-399: ‘Significant positive linear relationships were found between SOC increment and cumulative C input to the soils over the experimental period (Fig. 4)’ has been deleted.

Line 405: ‘slope of the relationship’ has been revised as ‘The slope of linear equation’.

Line 406: ‘...is retained (sequestered) in the soil (the sequestration efficiency)’ has been changed to ‘...is retained in the soils’

Line 407: Yes, it means for each 1 Mg C ha⁻¹ more input, SOC stock to 20-cm increased by 0.07 - 0.16 Mg C ha⁻¹.

Line 407: the sentence ‘The results suggest that differences between regions in the rate of SOC gain following the various fertilizer treatments were the result of differences in rate of SOC decomposition and thus retention and not just C inputs’ has been deleted as it was speculative.

Line 410: ‘sequestration efficiency’ has been changed to ‘retention rate of a site’

Line 410:

Comments: ‘R²=0.48’ Indicates poor explanation.

Authors’ response: In this sentence, we presented that the initial SOC stocks do not related to its retention rate, thus we thought the poor ‘R²’ here is appropriate.

Line 410: Because there are no proper references, thus we have changed ‘suggesting’ to a possible reason as ‘this may due to the differences in retention rate were largely the result of differences in climate or soil factors other than initial C content.’

Line 413-419: The sentence has been revised as ‘The range of sequestration efficiencies was similar to that observed from the Indian humid subtropical plains at 20-cm depth under a rice-wheat over 20-30 years (7.6-14%, Majumder et al., 2008) and a rice-lentil (*Lens culinaris*) system (9.9%, Srinivasarao et al., 2012), but lower than that from the temperate region of North America (14-21%, Rasmussen and Collins, 1991) and higher than that from topsoil of subtropical regions under a rice-wheat-jute (*Corchorus olitorius* L.) system (4-5%, Majumder et al., 2007).’

Line 420: The first paragraph ‘Soil organic matter is important in maintaining soil structure, porosity, water infiltration and retention, and can improve soil chemical buffering capacity,

biological activity and nutrient cycling (Loveland and Webb, 2003; Johnston et al., 2009; D'Hose et al., 2014; Oelofse et al., 2015). Quantifying the effect of SOC storages on crop yield has, therefore, become increasingly important in the context of ensuring food security (Lal 2004). Previous studies reported that SOC storages was positively correlated with crop yield in a range of production environments (Bauer and Black, 1994; Rasmussen and Parton, 1994; Cotching et al., 2002; Farquharson et al., 2003; Pan et al., 2009; Yan and Gong, 2010). However, others have found no significant correlation between changes in SOC and crop yields (Beyer et al., 1999; Oelofse et al., 2015) or that the correlation depends on the type of farming system (organic versus conventional; Brock et al., 2011)'has been deleted.

Line 421: 'problematic' has been changed to 'difficult'.

Line 421-422: 'SOC' has been changed to 'SOC stocks'.

Line 424: 'also alter the supply of nutrients' has been revised as 'also alter the supply of nutrients alongside effects on soil structure and water holding capacity etc.'

Line 431: 'pooled' has been changed to 'combined'.

Line 432: 'an apparent threshold' has been changed to 'apparent maximal yield-responsive SOC stocks'.

Line 435-460: We have added some references and discussions.

Line 466: 'concentration' has been changed to 'concentrations (ranged from 0.5% to 1.9%)'.

Line 467: '2%' has been changed to '2% to 0-20 cm soil depth'.

Line 470: 'discussed above' has been changed to 'to the northern regions'

Line 477: A reference has been added.

Line 481: 'If this is the case then it is clear the same restrictions and dependency on SOC are not found in the more temperate northern regions' has been deleted.

Fig legends

Line 742: 'Long-term trials' has been changed to long-term experiments throughout the text.

Line 747: 'N/A' means that there was no NPS treatment in the North east, North and South region. We have added the description in the legend.

Line 760: We have redrawn the Figure 4 by analyzing the relationship between change rates of SOC stocks ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$) and annual C inputs.

Tables

We have revised all the suggestion and correction following your comments.

Table S1: The data (except climate data) were all collected from the experiments. In addition, we have added a note in the table 'Note: Climate data were collected from the China meteorological sharing service system (<http://cdc.cma.gov.cn/>)'

Table S2: The data were all collected from the experiments. And the units have been placed beneath the elements.

Table S3: 'N/A' has been changed to 'None'.

Reviewer #5: Manuscript no. STOTEN-D-16-00432

Soil carbon sequestration in agricultural soil is important in terms of productivity and improvement of fertilizer use efficiency. Though worldwide diverse results came in terms of productivity enhancement with respect to SOC sequestration. But its importance is unquestionable. More and more studies are required for quantification of yield improvements and stability through improvement of root zone carbon in different crops/cropping systems throughout the world. Under this context, this study is relevant. But the study has more regional importance.

Authors' response

Many thanks for your constructive comments. We have revised the MS following the comments and responded the questions below:

Title:

Cropping system and Location (country name) can be included in the title to make it clearer. More emphasis in the paper was on effects of fertilization strategies on soil organic carbon storage- that may be emphasized in title itself.

Authors' response

Many thanks for your suggestion. The title has been revised as 'Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: evidence from long-term experiments with wheat-maize cropping systems in China'.

Introduction:

Recent findings should be included.

Introduction should also have the effects of fertilization strategies on soil organic carbon storage related research findings.

Authors' response

Many thanks for the comments. We have rewritten part of the introduction and added the review of fertilization strategies impact on SOC (Line 79-88). The references in year 2015 have been added in line 81.

Method and Material:

Data and statistical analysis- Crop Relative Yield for minimizing the influence of crop variety and climatic variation should be explained elaborately. It's not very clear.

Authors' response

Many thanks for the comments. We have been revised the description of relative crop yield in line 239-248.

Treatment details should be given. In chemical fertilizers: dose, time of application and source of application. In organic manure, how it was applied? what is the amount? Is it dry weight basis or wet weight basis etc.

Authors' response

Many thanks for the comments. The doses of chemical fertilizers (N, P and K) have been added in table 1. Time and source of application have been added in line 159-161. Organic manure was applied to surface of soils and it was wet weight basis.

Equation no. 4 (A and B parameters) and Equation no. 6 -Fitted parameters are not defined

anywhere so replicating the work will not be possible.

Authors' response

Many thanks for the comments. We have added the description of parameters in equation 4 and 6 to line 252-253 and line 269-270.

Results and Discussion:

I am doubtful about the analysis of the result. Better to use PCA for this as yield depends on lot of variables mainly soil type and texture, pH etc.

Soil classification also shows wide difference between soil types eg. Regosols, Cambisols are developing soil with very less or no profile development (in south), in north calcareous Cambisols, in north east Sod organic-accumulative and in north west accumulation of organic matter, high base status soils. How these are compared? Probably by PCA we can get the real picture that how sequestered carbon affects crop productivity and stability.

Authors' response

Many thanks for the constructive comments of the manuscript. We have considered the principal component analysis to explain our results. However, the PCA only show us SOC stock is one of the most important factors on crop productivity which have been reviewed in the introduction section, but not how SOC stock impact on crop yield. In our MS, the main objective was to establish the relationships between SOC and relative yield and yield stability and to determine whether these differed between regions. Thus, we did not use the PCA in the MS.

Why relative yield is increased in south than in north? It is not clearly discussed.

Authors' response

Thanks for the comments. We have re-discussed in line 468-477.

In North east SOC storage is more but yield is less why?

Authors' response

Thanks for the comments. Firstly, the 'yield' is the relative yield that actual yield of either wheat or maize from a treatment at a site in a year divided by yield in NPK at the site in the year. In the North east, the crop yield in the NPK treatment was not significant differed from the yield in the manure applied treatments, which not like that in the other regions that crop yield in the NPK treatment was lower than that in the manure applied treatments. Therefore, the relative yield is less in the North east than those in the other regions.

In Fig. 6 also north east is not showing any clear trend line for yield stability, discussion part is not clear.

Authors' response

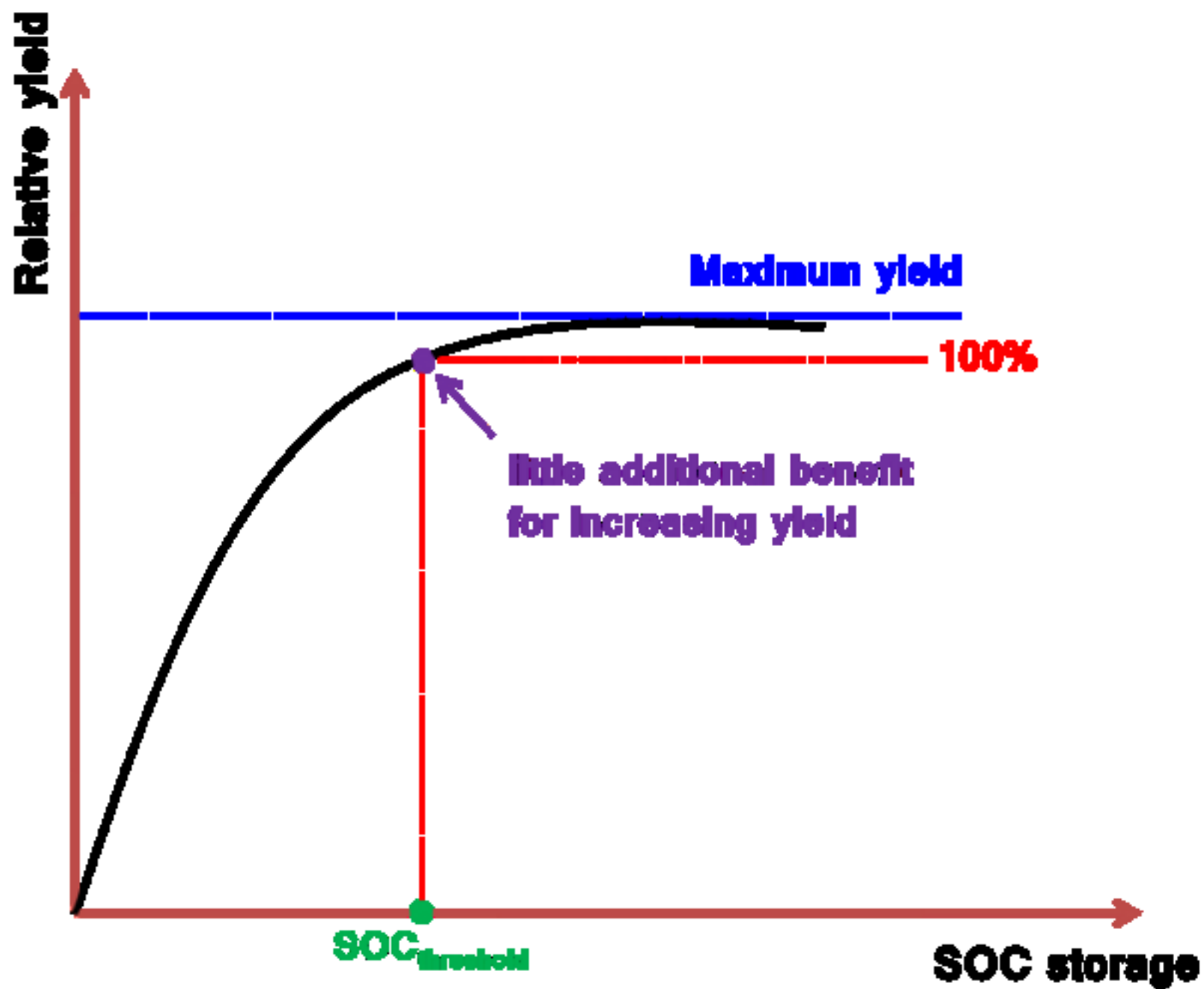
Thanks for the constructive comments. We have re-discussed in line 503 to 523.

References:

Year 2014 (only one reference) and 2015 references may be included.

Authors' response

The references in year 2015 have been added in line 81, 441 and 456.



Research Highlights

- 7.4-13.1% of total C input over 20-30 years was accumulated as soil organic C in the top 20 cm of soil
- SOC had relatively little impact on crop yield and its stability in northern China
- SOC significantly improved crop yield and its stability in southern China
- In south of China yield and its stability increased with SOC stocks up to a value of $\sim 35 \text{ Mg C ha}^{-1}$

**Effects of enhancing soil organic carbon sequestration in the topsoil by
fertilization on crop productivity and stability: evidence from long-term
experiments with wheat-maize cropping systems in China**

Xubo Zhang ^{1,2}, Nan Sun ^{1*}, Lianhai Wu ², Minggang Xu ^{1*}, Ian J Bingham ³,
Zhongfang Li ⁴

¹ *Ministry of Agriculture Key Laboratory of Crop Nutrition and Fertilization, Institute
of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural
Sciences, Beijing 100081, China.*

² *Sustainable Soils and Grassland Systems Department, Rothamsted Research, North
Wyke, Okehampton, Devon EX20 2SB, UK.*

³ *Crop & Soil Systems Research, SRUC, Kings Buildings, West Mains Rd, Edinburgh
EH9 3JG, UK*

⁴ *Chemistry and Bioengineering College, Hezhou University, Hezhou 542899, China.*

* Corresponding author:

xuminggang@caas.cn , sunnan@caas.cn

Tel.: +86 10 82105636; FAX: +86 10 82106225;

Abstract

Although organic carbon sequestration in agricultural soils has been recommended as a ‘win-win strategy’ for mitigating climate change and ensuring food security, great uncertainty still remains in identifying the relationships between soil organic carbon (SOC) sequestration and crop productivity. Using data from 17 long-term experiments in China we determined the effects of fertilization strategies on SOC stocks at 0-20 cm depth in the North, North East, North West and South. The impacts of changes in topsoil SOC stocks on the yield and yield stability of winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) were determined. Results showed that application of inorganic fertilizers (NPK) plus animal manure over 20-30 years significantly increased SOC stocks to 20-cm depth by 32-87% whilst NPK plus wheat/maize straw application increased it by 26-38% compared to controls. The efficiency of SOC sequestration differed between regions with 7.4-13.1% of annual C input into the topsoil being retained as SOC over the study periods. In the northern regions, application of manure had little additional effect on yield compared to NPK over a wide range of topsoil SOC stocks (18 - >50 Mg C ha⁻¹). In the South, average yield from manure applied treatments was 2.5 times greater than that from NPK treatments. Moreover, the yield with NPK plus manure increased until SOC stocks (20-cm depth) increased to ~35 Mg C ha⁻¹. In the northern regions, yield stability was not increased by application of NPK plus manure compared to NPK, whereas in the South there was a significant improvement. We conclude that manure application and straw incorporation could potentially lead to SOC sequestration in topsoil in China,

42 but beneficial effects of this increase in SOC stocks to 20-cm depth on crop yield and
43 yield stability may only be achieved in the South.

44

45 **Keywords:** Soil organic carbon; yield; yield stability; manure application; straw
46 return; China

1. Introduction

Soil organic carbon (SOC) can play an important role in increasing crop productivity, improving soil fertility (Tiessen et al., 1994), reducing atmospheric carbon dioxide (CO₂) enrichment (Lal, 2004), and providing other ecosystem services, such as improved soil structure and water retention (Fan et al., 2013a). Low SOC stocks could reduce crop yield through effects on soil fertility and significant nutrient loss may also occur as a result of low nutrient buffer or retention capacity. Changes in SOC stocks have been reported extensively on the global (FAO, 2001), regional (Huang and Sun, 2006; Smith, 2004) and plot scales (Zhang et al., 2010), which suggests that society has paid increasing attention to the potential for sequestering organic carbon in soils in an effort to mitigate climate change and promote crop productivity. For example, it has been reported that a 1% increase in SOC content of the topsoil (0-20 cm) could increase cereal yield by 430 kg ha⁻¹ and reduce yield variability by 3.5% (Pan et al., 2009). However, others have argued that claims about the potential benefits of increasing C inputs to the soil must be made with caution because of the uncertainties regarding how much can be sequestered under different climates and soil types (Brock et al., 2011; Manlay et al., 2007; Seremesic et al., 2011). Therefore, it is imperative to quantify the relationships between C inputs, SOC sequestration and crop productivity.

In the last three decades, China has been facing a challenge to ensure crop production is increased while mitigating greenhouse gas (GHG) emissions. China uses only 7% of the world's arable land to feed 22% of the global population (Fan et al., 2010) and produces over 20% and 17% of the world's maize (*Zea mays L.*) and

wheat (*Triticum aestivum* L.) grain, respectively (FAO, 2010). If China intends to maintain the policy of grain self-sufficiency, crop productivity has to be increased without reducing soil fertility including SOC content, one of the indicators for ensuring crop production (D'Hose et al., 2014). Currently, the average SOC concentration in the root zone of croplands (about 10 g C kg⁻¹) in China is much lower than that (25-40 g C kg⁻¹) in Europe and the United States (Fan et al., 2010). Furthermore, SOC losses from China's croplands have been widely reported (Huang and Sun, 2006; Qin et al., 2013; Sun et al., 2010). SOC stocks of agro-ecosystems may be increased by improving agronomic practices. Applications of animal manure and the incorporation of straw in the soil are recognized as SOC-enhancing management options (Lu et al., 2009; Tian et al., 2015). It has been reported that SOC stocks in the top 20 cm of the world's soils increased by 0.24-0.46 Mg C ha⁻¹ yr⁻¹ with a decade of manure application (Gattinger et al., 2012). In addition, it was reported that in Southern China SOC in the topsoil (0-20 cm) increased by 3.8 Mg C ha⁻¹ following manure application for 22 years compared with soils receiving mineral fertilizers alone (Huang et al., 2010). It has also been estimated that an additional 3.8 Tg C yr⁻¹ could be sequestered in soil if all of the straw generated from arable fields in China were returned to the soils (Lu et al., 2009).

It is challenging to quantify the contribution of SOC to either maintaining or stabilizing crop yield, as the contribution could be concealed by other factors given the complex interactions that occur between soil, root systems and canopies (Bingham, 2001). Most studies conducted across the world have suggested that there is some

linear relationship between SOC **stocks** in the root zone and crop yield and **its** stability (Bauer and Black, 1994; Beyer et al., 1999; Lal, 2010; Smith, 2004). However, a significant non-linear relationship has been reported between relative **crop** yield and **SOC in the root zone** (Lal, 2009), which implies that there is an upper value of SOC stocks **in the root zone** beyond which there will be no additional benefit on crop yield of increasing SOC stocks (Loveland and Webb, 2003; Krull et al., 2004). For example, crop yields did not increase any further when **SOC content in the topsoil** exceeded 2 % in the upland soils of Alberta, Canada (Krull et al., 2004). Moreover there could be potential hazards of adding too much C to soils, such as surface crusting, increased detachment by raindrops, decreased hydraulic conductivity (Haynes and Naidu, 1998) and water-repellency (Olsen et al., 1970). Addition of excessive amounts organic materials to soils could also lead to **losses** in soil nitrogen (N) and/or phosphorus (P), resulting in surface and ground-water pollution (Patrick et al., 2013).

Determining the upper value of SOC **stocks** would provide guidance for designing management practices to **optimise crop yields** and mitigate climate change. However, there are few studies to date that have examined the relationship between **SOC stocks and crop productivity**, and quantified the maximal yield-responsive SOC stocks based on long-term observations (Lal, 2006; 2010). The objective of **this** research was to analyse datasets from 17 long-term fertilization experiments across China to: 1) determine the impact of different fertilizer application and straw management strategies on **SOC sequestration in topsoil (0-20 cm)** in different **regions**; 2) to establish the relationships between **SOC stocks to 20-cm depth** and crop yield

and yield stability for the different regions; and 3) to determine whether the maximal yield-responsive SOC **stocks** for enhancing cereal yields differs between regions. The overall aim of the research was to establish whether soil management practices to **optimise yield** and yield stability should be modified for specific regions.

2. Methods and materials

2.1 Long-term fertilization experiments

Datasets collected at 17 long-term fertilization **experiments** established between 1979 and 1990 in arable **lands** across China were used for this study (Fig. 1 and Table S1). Four sites **were** located in the North East region: Haerbin (HEB), Gongzhuling (GZL-A and -B), and Shenyang (SY); four in the North West region: Urumqi (UM), Zhangye (ZY), Pingliang (PL) and Yangling (YL); five in the North region: Changping (CP), Tianjin (TJ), Yucheng (YC), Zhengzhou (ZZ) and Xuzhou (XZ); and four in the South region: Suining (SN), Chongqing (CQ), Qiyang (QY) and Jinxian (JX).

Climatic conditions, and soil properties at the beginning of the experiments are presented in Tables S1 and S2. Various climatic types are represented in these regions. Annual average temperatures varied from 3.5 °C at the HEB site to 18.3 °C at the CQ site. Annual precipitation ranged from 127 mm at the ZY site (in the arid area) to 1581 mm at the JX site in the humid monsoon climate zone. Annual pan evaporation varied from 990 mm at the CQ site to 2570 mm at the UM site (data from China meteorological sharing service system, <http://cdc.cma.gov.cn/>). Annual evaporation at

the sites in the South region was almost the same as annual precipitation. However, it was much higher than annual precipitation in the other regions (Table S1). Irrigation was applied at the majority of sites in the North and North West (Table S1).

2.2 *Management of the field experiments*

A detailed description of the cropping systems is shown in Table 1. A monoculture cropping system was practiced at the GZL-A and -B, SY, and PL sites with continuous maize, while a rotation of winter wheat-winter wheat-maize (i.e., two wheat seasons followed by a maize season) at the ZY and UM sites. However, the rotation at site ZY changed once between 1994 and 1997, i.e., three continuous wheat seasons followed by one maize season. A double cropping system was practiced at the other sites; at JX it was maize-maize, at SN and CQ it was wheat-rice (*Oryza sativa L.*), whilst at the remaining sites it was summer maize-winter wheat. At all sites, weeds were removed manually and pesticides were applied when needed to control insect pests and fungal diseases.

Four types of treatments common among all sites were chosen for this study: (i) unfertilized (thereafter, Control); (ii) inorganic N, P and/or potassium (K) fertilizer combined (hereafter referred to as, NP and NPK); (iii) inorganic NP and NPK plus wheat or maize straw returned (hereafter, NPS and NPKS); and (iv) inorganic NP and NPK plus animal manure (hereafter, NPM and NPKM) or 1.5-2.0 times amount of N in manure only or of total N application (hereafter, hNPKM) used in the NPKM treatment. The application rate of inorganic N (urea), P and K fertilizer that could ensure high crop yield at a particular site was set according to recommended rates for

commercial crops in the regions (NP and NPK; Table 1). The inorganic N, P and K fertilizers were applied five to seven days before sowing. The fertilizer-N strategy in the NPM and NPKM treatment differed between sites. At HEB, GZL-B, SY, CP, YC, XZ, ZY, PL, SN, CQ and JX sites the same amount of inorganic N was applied as in the NP and NPK treatments, **thus**, at these sites the NPM and NPKM treatments received additional N from manure. At GZL-A, TJ, ZZ, UM, YL and QY, the same amount of total N was applied to NP/NPK and NPM/NPKM treatments at a given site, with 30-50% of it from inorganic N-fertilizer when manure was added (i.e., NPM/NPKM) For the NPS and NPKS treatments, maize and wheat straw **was** chopped and incorporated into the soil (**0-20 cm depth**) immediately after harvest. N content in straw, was deducted from the total amount of fertilizer-N applied at GZL-A and UM (1995 onwards) so that the total N applied was the same as that received by NP and NPK treatments at these sites. At remaining sites no deduction was made, because the information on N content in straw could not be provided in time for when fertilizers were applied. Micronutrient fertilizers containing boron, zinc, manganese, magnesium and iron were applied across all treatments at the QY site every two to four years to avoid potential deficiencies.

The treatments with large **plots** ($>100\text{m}^2$, Table S3) did not have replicates except those at the SY, PL, and QY sites. Otherwise, the treatments had two to four replicates (Table S3). At all sites, 100cm depth cement baffle plates were erected along the boundaries of each plot to avoid lateral exchange of water and nutrients between adjacent plots. The treatments were initially randomized at each site and then that

treatment was fixed to the plot in the following years.

2.3 Soil and Plant Sampling and Analysis

Soil samples were collected from the top 20cm soil depth at the beginning of the experiments, and then annually from each plot approximately 15 d after harvest. As the plough depth ranged from 20-25 cm across sites and regions, the depth of soil sampling represents the minimum plough depth for the study. Twenty cores from each plot were collected randomly using a soil auger (5 cm diameter) and the soil from a random four cores combined, which formed five samples for each plot. Air-dried soils (~20 kg, 7 d) were sieved through a 2 mm screen to determine pH (1:1 w/v water) and other soil properties. Sub-samples were crushed to 0.25mm for the measurements of SOC, total N (TN), total P (TP), and total K (TK). SOC content was determined by sulphuric acid-potassium dichromate oxidation (Walkley and Black, 1934). TN was determined by the method described by Bremner and Mulvaney (1965), TP by Murphy and Riley (1962), and TK by Kundsén et al. (1982). Available N was measured following the method of Jackson (1958). Available P was determined by the Olsen-P method (Olsen et al., 1954) and available K by the method of Shi (1976). The contents of TN, TP, and TK in manure were measured following the procedures described by Mahimairaja et al. (1994), Barnett (1994), and Wen et al. (1997), respectively. Soil bulk density was measured by using steel ring with 5-cm diameter, and soil samples were taken at 10 cm depth, dried at 105 °C for eight hours and then weighed (SSSC 2000).

Maize and wheat plants were harvested manually close to the ground with sickles

and all harvested materials were removed from the plots for all the treatments except the NPS and NPKS treatments. Thus, only roots and shed leaf litter were left on the plots. The harvested plants were air-dried, threshed, and oven-dried at 70°C to constant dry weight. For each treatment plot, five samples from the dried straw and grains each were collected for the measurement of nutrient contents. Sampled dry matter was digested with H₂SO₄-H₂O₂, and the concentrations of TN, TP and TK in the digesting solution were measured using the micro-Kjeldahl method, colorimetric analysis and dissolution-flame photometry, respectively (Page et al., 1982). For the NPS and NPKS treatments, the crop residues were chopped and incorporated into the soils (0-20 cm) by disking immediately after harvest each year. Grain yield from a plot was determined from each whole plot.

2.4 Carbon inputs from crops

It was assumed that the annual biomass input from roots, exudation and dead materials by wheat and maize is 30% of aboveground dry matter (Kundu et al., 2007; Zhang et al., 2010), and that 75 and 85% of the total root biomass was in the surface 20 cm of the soils for wheat and maize, respectively (Jiang et al., 2014). 39.9 and 44.4 g C kg⁻¹ (dry matter), as a national average (NCATS, 1994), were used to represent the C contents in dry matter for wheat and maize, respectively. For the NPKS treatment, C contents in maize and wheat straw were set to 12.4 and 27.8 g C kg⁻¹ (fresh weight), respectively (Zhang et al., 2010).

2.5 Statistical analysis

SOC concentration (SOC_C) in the top 20 cm of the soil was converted to SOC stock (SOC_S , Mg C ha⁻¹):

$$SOC_S = SOC_C \times d \times BD \times 10 \quad (1)$$

where d is the soil depth (0.2 m), BD is the soil bulk density (g cm⁻³) and 10 is a unit conversion factor.

SOC_S in a given year can also be expressed as a function of the number of the years since an experiment started (Y_n):

$$SOC_S = aY_n + b \quad (2)$$

where a represents the rate of change in SOC stocks (Mg C ha⁻¹ yr⁻¹) in the top 20 cm depth and b is the SOC stocks at the beginning of the experiment. A similar expression was applied to crop yield (Y_{grain}). However, the slope a represents the rate of change (kg ha⁻¹ yr⁻¹) of crop yields and the intercept b is the initial crop yield. Linear regression was used to fit these functions and the residuals examined to determine the suitability of a linear model. There was no evidence of non-linearity for any of the sites.

As the dataset from long-term experiments in different regions or cropping systems cannot be compared directly, relative crop yield (YR) was used to minimise the influences of crop variety replacement, seasonal variation in weather conditions and changes in agronomic practices during the study period and to make the dataset from individual experiments more comparable. YR was calculated based on the annual

data from the long-term experiments across the four regions.

$$YR = \frac{YE}{Y_{NPK}} \quad (3)$$

where YE is the actual yield of either wheat or maize from a treatment (kg ha^{-1}) at a given site in a given year and Y_{NPK} is the yield of the crop from the NPK treatment at the same site in the same year.

To obtain the maximal yield-responsive SOC_s (SOC_{opt}) for relative crop yield, the linear-plateau model was chosen to quantify the relationship between YR and SOC_s in a given year (Bai et al., 2013; Lal, 2010):

$$YR = \begin{cases} A \cdot SOC_s + B & (SOC_s < SOC_{opt}) \\ YP_{max} & (SOC_s \geq SOC_{opt}) \end{cases} \quad (4)$$

where A means that the relative yield increment per 1 Mg C ha^{-1} SOC increment and B is the relative yield at the initial SOC level in an experiment site; SOC_{opt} (Mg C ha^{-1}) is the upper value of SOC beyond which there is no additional benefit for relative crop yield of increasing SOC stocks further; YP_{max} is the predicted plateau maximum relative yield and fitted with the data. Models were fitted using Genstat (version 16th Edition, 2013, VSN international Trust, Hemel Hempstead, UK).

The stability of grain yield for a treatment was evaluated by its variability (CV , %) (Pan et al., 2009):

$$CV = \frac{Y_{std}}{Y_m} \times 100 \quad (5)$$

where Y_{std} is the standard deviation of the yields of a particular treatment at a site over

the whole experimental period and Y_m is the mean yield for the treatment within the same period. Differences between regions were then compared using values of CV averaged across sites within regions.

The exponential decay equation was used to characterize the relationship between the average SOC_s under a given treatment and yield variation during the experimental period:

$$CV = \beta_0 + \beta_1 e^{-\beta_2 SOC_s} \quad (6)$$

where β_0 is the lower value of CV (lower value of asymptotic line), $\beta_0 + \beta_1$ is the maximum value of CV and β_2 is the rate of decrease of CV.

One-way ANOVA was applied to test the significance of the effects of fertilizer treatments on the average relative yields and SOC storage within the regions. Differences between specific treatments within a region were compared with the least significant differences (L.S.D) at either the 5% or 1% level of probability depending on the analysis. Simple linear regression with groups (Genstat version 16th Edition, 2013, VSN international Trust, Hemel Hempstead, UK) was used to compare the slopes of the relationships between total cumulative C input and the increase in SOC storage between regions. With the exception of fitting linear-plateau models and linear regression with groups (above), all statistical analyses were performed with SPSS v. 17.0 for Windows (SPSS, Inc., 1999, Chicago, USA, www.spss.com). Prior to analysis residuals were checked for homogeneity of variance and normality to ensure that they satisfied the assumptions of parametric tests.

3. Results

3.1 Crop yield and stability

The mean annual rates of change in crop yields over time under the different fertilization strategies at each site are shown in Table 2. At all sites but SY (where there was an increase) crop yield in the control (unfertilized) treatment either did not change or decreased on average over time. The trends for the other treatments were more variable with both positive and negative changes in mean annual yields over the study periods. For application of NPK fertilizer, 37% of the site-crop combinations showed a positive yield trend, whilst 22% showed a negative yield trend. When manure was applied this proportion was 51% (NPKM) and 67% (hNPKM) of site-crops with positive yield trends and only 11 and 6%, respectively, with negative trends.

When averaged over the experimental period, the yields of wheat relative to the NPK treatment showed a similar pattern in all the regions (Table 3). The highest relative yields were in the manure applied treatments, followed by NPKS. The relative yields were significantly ($P < 0.05$ LSD) greater than the NPK reference in the North West and South, but not the North East and the North indicating that in two out of four regions there was a yield response to application of manure over and above that observed with inorganic NPK. Addition of manure resulted in an improvement in relative yields compared to straw (NPKS) only in the North and South. Yields for the NP treatment were marginally lower than those of the NPK reference in the northern

sites (6-12%; $P < 0.05$ for the North and North West) indicating only a small increase in yield in response to application of K fertilizer. However, the response was greater (12% $P < 0.05$) in the South. Unfertilized controls had yields lower than those for the other treatments.

The relative yields of maize responded in a similar way to fertilizer treatment as those for wheat. By far the greatest benefits to yield from manure additions were found in the South. Smaller ($P < 0.05$) benefits over NPK were found in the North East and North West. The beneficial effects on yield of returning straw to the soil were observed only in the South (Table 3).

Annual yield variation (CV %) was around 20 to 30% for wheat and maize in the North East region, and did not differ between treatments (Fig. 2). In unfertilized controls wheat and maize yield variability in the North and North West was greater (CV approximately 35%) than in the North East ($P < 0.05$), and declined ($P < 0.05$) with the addition of inorganic fertilizer and manure. Thus, the average yield variability of the NPM, NPKM and hNPKM treatments was less (yield was more stable) than that of the control treatment in the North and North West. In the South, yield variability was considerably greater (CV $> 60\%$) than in the northern regions when no fertilizer was applied. Moreover application of NP and NPK did not reduce this variability unlike the response in the northern regions. Applications of manure (NPM, NPKM, hNPKM) reduced yield variability to values comparable to the other regions (CV $\sim 20\%$). By contrast, straw incorporation (NPS, NPKS) did not cause a reduction in yield variability to the same extent as manure.

3.2 *Topsoil SOC stocks and C inputs*

In order to compare the effects of fertilizer treatments on SOC stocks (i.e. contents), SOC at beginning and end of the experimental period in different regions were compared (Table 4). Average SOC stocks for the Control treatment at the beginning of experiments was the lowest among the treatments in all the regions (19.3-31.9 Mg C ha⁻¹) and the value decreased in the North West and North regions over the whole experimental period, but not in the North East and South. The inorganic fertilizer treatments NP and NPK had relatively small effects on SOC stocks over the experimental period in the North East region. In the other regions, however, SOC stocks in the NP and NPK treatments increased ($P<0.05$). By contrast addition of manure (NPM, NPKM and hNPKM) led to an increase ($P<0.05$) in SOC relative to controls and inorganic fertilizer treatments in all regions ($P<0.05$). Averaged across manure treatments the increases in SOC from beginning to end of experiments were 18, 43, 14 and 23% in the North East, the North West, the North and the South region, respectively. The average SOC stocks from the NPKS treatment at the end of experiments were higher ($P<0.05$) than that at the beginning of the experiments in all the regions. Moreover, the increases in SOC stocks were smaller following straw incorporation than following addition of manure in all regions.

Regional averages of SOC stocks mask considerable variation in SOC dynamics between individual sites. The rates of change in SOC stocks to 20-cm depth under different fertilization strategies at each site are shown in Table 5. With the exception of the CP, YC and YL sites there was either no change (9 sites) or a decrease (5 sites)

in SOC stocks over time in the unfertilized Control treatment. With NPK there was an increase (5 sites), no change (10 sites) or a decrease (1 site) over 20 to 30 years. By contrast, manure application and straw incorporation resulted in an increase ($P < 0.05$) of 0.18-1.38 and 0.18-0.62 Mg C ha⁻¹ yr⁻¹ respectively at over 80% of the monitored sites. Further, at sites where there was an increase in SOC stocks over time without fertilizer, the rate of increase with additions of manure and straw were approximately 2 to 7 fold greater.

Average annual C inputs from crops and manure for different treatments in all four regions are shown in Fig. 3. Input of C from crops where only inorganic fertilizer was applied (NP and NPK) was approximately double that of the Control treatment in each of the regions. Furthermore, there were no differences in annual C input from crops between the inorganic fertilizer, manure application and straw incorporation treatments. Total C input to the soil was greater where manure was applied and straw returned to the soil compared with plots receiving inorganic fertilizer only.

In addition, positive linear relationships between change rate of SOC stocks and annual C inputs to the soils over the experimental period were found (Fig. 4). The slopes for the regions ranged from 0.074 to 0.131 which indicated that 7.4% to 13.1% of the annual C inputs could be sequestered in the soils. The slopes differed significantly ($P < 0.05$) between regions, with the retention rate of C inputs in the North West being greater than that in the South and North East.

3.3 Responses of crop yield and yield stability to changes in topsoil SOC stocks

Data from individual treatments and sites within a region were combined to examine

the relationship between SOC stocks and relative yield. Significant correlations between SOC stocks and relative yield were found with an apparent maximal yield-responsive SOC stock (SOC_{opt}) above which there may be no increase in relative yield (Fig. 5). YR_{max} determined with the linear-plateau model ranged from 1.14 to 1.43 for wheat and from 1.13 to 2.06 for maize. The greatest relative yields were observed in the South region. The corresponding values of SOC_{opt} were 46.2, 26.5, 21.8 and 34.7 Mg C ha⁻¹ for wheat and 44.4, 28.0, 22.0 and 34.8 Mg C ha⁻¹ for maize in the North East, the North West, the North and the South region, respectively.

Relationships between the variability of wheat and maize yields and the average SOC stocks over experimental period are shown in Fig. 6. There was no correlation in the North East region. However, in the other three regions, with the increase in SOC stocks, the yield variability for both wheat and maize showed a relatively weak (r^2 0.38-0.59) exponential decrease, i.e. yield stability increased with increases in topsoil SOC stocks.

4. Discussion

4.1 Impact of fertilization management on topsoil SOC stocks

Whether or not organic C can be retained in soils depends on the balance between C input and output as influenced by agronomic practices (e.g., fertilization, straw return, rotation, tillage, etc.) and climatic conditions. Results from the present study show that N fertilizer application and organic soil amendments influenced the rate of C sequestration, and that rates differed between regions and sites within regions because of differences in soil type, management and climate which can impact on the retention

of SOC in soils (Gabriel and Kellman, 2011; Gattinger et al., 2012; Lu et al., 2009; Six et al., 2002). Balanced application of inorganic N, P, and K fertilizers increased SOC stocks at four out of five sites in the North, but at only one site in the North West and none in the North East and South regions. The annual rates of change of SOC to 20-cm depth for the regions were broadly consistent with those reported by Lu et al. (2009) when compared at similar application rates of N. By contrast, straw incorporation and application of animal manure led to more consistent increases in SOC stocks at the 20-cm soil depth across sites and regions, with the average rate from manure application ($0.67 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) being over twice that from straw incorporation ($0.29 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) for sites where both treatments were included (Table 5).

The slope of the linear relationship between SOC increment and cumulative C input to soils can be considered as the proportion of total C input that is retained in the soils, which ranged from 7.4 to 13.1% between regions. In fact, for a given treatment, estimated annual C inputs differed relatively little between regions (Fig. 3). Moreover, there was only a weak association between the average initial soil C stock of a region and its C retention rate ($P = 0.19$, $R^2 = 0.48$ data not shown), suggesting that the observed differences in retention rate between regions were largely the result of differences in climate or soil properties rather than the initial topsoil SOC stocks. The range of sequestration efficiencies was similar to that observed from the Indian humid subtropical plains at 20-cm depth under a rice-wheat over 20-30 years (7.6-14%, Majumder et al., 2008) and a rice-lentil (*Lens culinaris*) system (9.9%, Srinivasarao et

al., 2012), but lower than that from the temperate region of North America (14-21%, Rasmussen and Collins, 1991) and higher than that from topsoil of subtropical regions under a rice-wheat-jute (*Corchorus olitorius L.*) system (4-5%, Majumder et al., 2007).

4.2 *Relative yield response to enhancement of SOC stocks*

Investigating the effects of SOC stocks *per se* on yield is difficult, because treatments designed to vary SOC stocks, such as the addition of organic matter, also alter the supply of nutrients alongside effects on soil structure and water holding capacity etc. (Bauer and Black, 1994; Johnston et al., 2009; D'Hose et al., 2014; Loveland and Webb, 2003; Oelofse et al., 2015). Moreover, analysis of relationships using long-term data sets are subject to large variation in yield arising from seasonal variation in weather conditions and changes in agronomic practices during the study period such as the crop rotation. We have minimised these sources of variation by expressing the yield observed under a specific treatment relative to the yield obtained in the same year and site with a full balanced (NPK) inorganic fertilizer supply. When data from the different fertilizer treatments and sites within a region were combined and relative yields plotted against topsoil SOC stocks, apparent maximal yield-responsive SOC stocks (SOC_{opt}) were obtained comparable to that reported by Krull et al. (2004) in a reworking of total biomass yields from sites in arable land of Canada.

In the present study SOC_{opt} values were derived from the fitting of a linear-plateau model to all data including those from unfertilized controls, and thus,

interpretation of the agronomic significance of the SOC_{opt} must be made cautiously.

The large increase in relative yield from values <1.0 to 1.0 is obtained over a narrow range of topsoil SOC stocks in each region and is associated with the application of NP and NPK fertilizer. These increases in yield can, therefore, be ascribed to the nutritional benefits of fertilizer supply (Oelofse et al., 2015; Pan et al., 2009). In the North, and North West, there was a small increase (4-15%) in average relative yield of wheat and maize with applications of manure (NPKM and hNPKM, Table 3), which was similar to the results reported by Beyer et al., (1999). As the rates of NPK applied were based on the recommended fertilizer rates required to satisfy the nutrient requirements of commercial crops in the region, the results suggest that manure applications may have had small beneficial effects on yield through the supply of other macronutrients in the northern regions such as S, micronutrients, or via effects on soil physical or biological properties (Zhang et al., 2010). Importantly, the effects appeared to occur independently of topsoil SOC stocks over a wide range from approximately 18 to >50 Mg C ha⁻¹ (0.72 – >2.0%). In this regard, when the effects of NPK supply are taken into account (i.e., when crops are supplied with inorganic NPK fertilizer) there appears to be no clear maximal yield-responsive topsoil SOC stocks for sustaining the yield of wheat and maize in the North and North West. It was reported that wheat and maize yields in plots supplied with animal manure did not differ from those given inorganic NPK for 33 years in the North of China (Yang et al., 2015). A similar interpretation can be made for the North East even though the linear-plateau model yielded a high apparent SOC_{opt} . The high SOC_{opt} results from the

greater variation in the data for this region, especially for unfertilized Controls, and lower coefficient of determination ($R^2 \leq 0.35$).

The concept of maximal yield-responsive SOC stocks has been proposed previously (Loveland and Webb, 2003; Krull et al., 2004), but it has been argued that the quantitative evidence for such an upper value(s) is weak, at least for soils in temperate climates (Loveland and Webb, 2003; Oelofse et al., 2015). Our data for the temperate regions of China support this view. It is worth emphasising too that the range of SOC concentrations (from 0.5% to 1.9%) measured in our soils was well below the threshold of 2% (to 0-20 cm soil depth) generally believed to be critical for maintaining soil functions (Loveland and Webb, 2003). However, our data also indicated that the response in the sub-tropical climate of the South region is appreciably different to the northern regions. In the South there was a marked increase in yield of both wheat and maize with application of manure plus inorganic NPK relative to inorganic NPK on its own (Table 3). Moreover, the relative yield increased with NPKM treatment as SOC stocks increased up to the SOC_{opt} of 35 Mg C ha⁻¹ (Fig. 5). It is conceivable that in the climate, soils and production systems of the South there is a more marked deficiency in the supply of nutrients other than NPK compared to the northern regions and that supply of animal manures and straw, or higher SOC concentrations are required to satisfy these requirements (Zhang et al., 2009, 2010). Alternatively, the restriction to yield may be from some aspect of soil physical quality associated with low SOC stocks (<35 t C ha⁻¹, 1.39 % dry weight) such as soil structure, drainage or soil water retention (Fan et al., 2013a) and that this is alleviated

as SOC is increased by addition of manure.

It can be estimated that the yields of wheat and maize crops in the South region could be increased by 89.6 and 252.4 kg ha⁻¹ respectively for each 1.0 Mg C ha⁻¹ increment in topsoil SOC up to SOC_{opt} . These rates are considerably higher than the 10 – 43 kg ha⁻¹ reported for cereal production in other areas of the world (Lal, 1981; Bauer and Black, 1994; Diaz-Zorita et al., 2002; Pan et al., 2009). Thus, based on average regional yields of wheat (3.1 Mg ha⁻¹) and maize (4.4 Mg ha⁻¹) in the south of China (National Bureau of Statistics of China, 2009), the yield of wheat could be increased by 1.94 and maize by 3.04 Mg ha⁻¹ if SOC stocks was increased to its SOC_{opt} . An additional 198 Mg C ha⁻¹ would need to be retained in soils in the south of China in order to fill the gap between current stock levels and SOC_{opt} . If SOC_{opt} is to be reached in the next 30 years at least 6.6 Mg C ha⁻¹ yr⁻¹ should be applied to the soil (most effectively as animal manure) given that 9% of the C input is sequestered (Fig. 4).

4.3 Yield stability vs. topsoil SOC stocks

Yield stability is an important indicator of agricultural sustainability (Katyal et al., 2001; Lal, 2004; Seremesic et al., 2011). Whether increasing SOC stocks can reduce yield variation is still a matter of debate (Pan et al., 2009; Pan et al., 2006; Yan and Gong, 2010). There is evidence that yield variability increases when crop growth and yield become more dependent on soil fertility to supply the required mineral nutrients (e.g. with zero or unbalanced inorganic fertilizer applications) (Yan and Gong, 2010).

Our data suggest that the extent to which this occurs may depend on the range of SOC stocks or other regional differences in soil and/or climatic conditions. Thus, in the North East there was little difference in the variability of wheat and maize yields between any of the fertilizer treatments (Fig. 2), even though the actual yield of unfertilized Controls was generally ~50-60% of that of crops receiving NPK (Table 3, Fig. 5). This implies that yields of unfertilized crops, although lower, were not more susceptible to seasonal variation in other abiotic and biotic stresses than fertilized crops. Furthermore, variation of wheat and maize yield did not show any clear trend, this may be because of beneficial effects of the high SOC stocks in soils in this region (30 - 45 Mg C ha⁻¹ average for the experimental period, Fig. 6) increasing crop resilience to biotic and abiotic stresses (Fan et al. 2013b), or an inherently lower seasonal variation in climatic conditions or pest problems in this region compared to others. In the North, North West and South, significant negative exponential relationships were found between topsoil SOC stocks and yield variation (Fig. 6). For the North and North West much of the reduction in variability (increase in stability) was associated with the supply of balanced NPK fertilizer (Fig. 2); there was relatively little further improvement with additions of animal manure and increases in SOC stocks above 18 and 25 Mg C ha⁻¹ for the North and North West, respectively. In the South, however, balanced fertilizer applications alone did not substantially reduce yield variability of either wheat or maize and, unlike the northern regions, there may be appreciable benefits for stabilizing yield of applying manure to raise the topsoil SOC stocks above 30 Mg C ha⁻¹.

524

525 **5. Conclusions**

526 This study shows that whilst there is significant potential for sequestering C in topsoil
527 across several regions of China through straw incorporation and application of animal
528 manure along with NPK fertilizer, there are strong regional differences in the benefits
529 of SOC stocks on the yield and yield stability of wheat and maize. We estimate that if
530 the same amount of manure and straw used in the experiments were applied to the
531 soils in the wheat and maize planted areas, 22.7 and 12.9 Tg C yr⁻¹ respectively could
532 be sequestered in the soils of the four regions studied. Moreover, there was no
533 evidence of the soils reaching saturation. However, in the North, North East and
534 North West, use of animal manure or straw to increase topsoil SOC stocks above
535 current values had relatively little benefit for yield and yield stability relative to the
536 application of NPK fertilizer. In the South, there were substantial yield responses to
537 applications of manure over and above those obtained with NPK and hence there is
538 potential for increasing yield, and improving yield stability, by using manure to
539 increase topsoil SOC stocks to the SOC_{opt} of 35 Mg C ha⁻¹. This could make a
540 significant contribution to improving agricultural sustainability in the region.

541 **Acknowledgements**

542 Financial support was from National Basic Research Program (2011CB100501),
543 National Key Technologies R&D Program (2012BAD14B04), National Science
544 Foundation of China (41171239) and Natural Science Foundation of China
545 (41371247). The authors acknowledge all colleagues from the long-term fertilization

experimental sites for their unremitting assistance. The authors also thank two anonymous reviewers for their constructive comments on an earlier version of this paper.

References

- Bai, Z., Li, H., Yang, X., Zhou, B., Shi, X., Wang, B., Shen, J., Chen Q., Qin, W., Oenema, O., Zhang, F. 2013. The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. *Plant soil*, 372: 27-37.
- Barnett, G.M., 1994. Phosphorus Forms in Animal Manure. *Bioresource Technol.* 49, 139-147.
- Bauer, A., Black, A.L., 1994. Quantification of the effect of soil organic-matter content on soil productivity. *Soil Sci. Soc. Am. J.* 58, 185-193.
- Beyer, L., Sieling, K., Pingpank, K., 1999. The impact of a low humus level in arable soils on microbial properties, soil organic matter quality and crop yield. *Biol. Fert. Soils* 28, 156-161.
- Bingham, I.J., 2001. Soil-root-canopy interactions. *Annals of Applied Biology* 138, 243-251.
- Bremner, J.M., Mulvaney, C.S., 1965. Nitrogen-Total. In: *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties* (ed. Black, CA), pp. 595-624, Am. Soc. Agron., Madison.
- Brock, C., Fliessbach, A., Oberholzer, H.R., Schulz, F., Wiesinger, K., Reinicke, F., Koch, W., Pallutt, B., Dittman, B., Zimmer, J., Hulsbergen, K.J., Leithold, G., 2011. Relation between soil organic matter and yield levels of nonlegume crops in organic and conventional farming systems. *J. Plant Nutr. Soil Sci.* 174, 568-575.
- Cotching, W.E., Hawkins, K., Sparrow, L.A., McCorkell, B.E., Rowley, W., 2002. Crop yields and soil properties on eroded slopes of red ferrosols in north-west Tasmania. *Aust. J. Soil Res.* 40, 625-642.
- D'Hose, T., Cougnon, M., De Vlieghe, A., Vandecasteele, B., Viaene, N., Cornelis, W., Van Bockstaele, E., Reheul, D., 2014. The positive relationship between soil quality and crop production: A case study on the effect of farm compost application. *Appl. Soil Ecol.* 75, 189-198.
- Díaz-Zorita, M., Duarte, G.A., Grove, J.H., 2002. A review of no-till systems and soil management for sustainable crop production in the subhumid and semiarid Pampas of Argentina. *Soil Till. Res.* 65, 1-18.
- Fan, M., Cao, J., Wei, W., Zhang, F., Su, Y., 2013a. Managing soil organic carbon for advancing food security and strengthening ecosystem services in China. In: *Ecosystem services and carbon sequestration in the biosphere.* (eds Lal R, Lorenz K, Hüttl RF, Schneider BU, Von Braun J), pp. 419-429, Springer Netherlands.
- Fan, M., Christie, P., Zhang, W., Zhang, F., 2010. Crop production, fertilizer use and soil quality in China. In: *Advanced in Soil Science: Food security and soil quality.* (eds Lal

R, Stewart BA), pp. 87-108, CRC Press, , London, New York.

Fan, M., Lal, R., Cao, J., Qiao, L., Su, Y., 2013b. Plant-Based assessment of inherent soil productivity and contributions to China's cereal crop yield increase since 1980. *Plos One* 8, e74617 doi:74610.71371/journal.pone.0074617.

FAO, 2001. Soil carbon sequestration for improved land management. World Soil Resources Reports, 2001, No 96, Food & Agric. Organization, Rome, Italy, ISSN, 0532-0488.

FAO, 2010. FAOSTAT Database - Agriculture Production. Rome: Food and Agriculture Organization of the United Nations.

Gabriel, C.E., Kellman, L. 2011. Examining moisture and temperature sensitivity of soil organic matter decomposition in a temperate coniferous forest soil. *Biogeosciences Discussion*. 8:1369-1409.

Farquharson, R.J., Schwenke, G.D., Mullen, J.D., 2003. Should we manage soil organic carbon in Vertosols in the northern grains region of Australia? *Aust. J..Exp. Agr.* 43, 261-270.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mader, P., Stolze, M., Smith, P., Scialabba, N.E.H., Niggli, U., 2012. Enhanced top soil carbon stocks under organic farming. *P. Natl. Acad. Sci. USA*. 109, 18226-18231.

GenStat 16th Edition, 2013. Service Pack 1 Version 16.2.0.11713. VSN international Trust, Hemel Hempstead, UK.

Haynes, R.J., Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutr. Cycl. Agroecosys*. 51, 123-137.

Huang, S., Peng, X., Huang, Q., Zhang, W., 2010. Soil aggregation and organic carbon fractions affected by long-term fertilization in a red soil of subtropical China. *Geoderma*, 154, 364-369.

Huang, Y., Sun, W.J., 2006. Changes in topsoil organic carbon of croplands in mainland China over the last two decades. *Chinese Sci. Bull.* 51, 1785-1803.

Jackson, M. L., 1958. Soil chemical analysis. pp. 183-204, Prentice-Hall, Inc. New York..

Johnston, A.E., Poulton, P.R., Coleman, K., 2009. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *Adv. Agron.* 101, 1-57.

Jiang, G., Xu, M., He, X., Zhang, W., Huang, S., Yang, X., Liu, H., Peng, C., Shirato, Y., Iizumi, T., Wang, J., Murphy, D.V., 2014. Soil organic carbon sequestration in upland soils of northern China under variable fertilizer management and climate change scenarios. *Global Biogeochem. Cy.*, 2013GB004746.

Katyal, V., Gangwar, K.S., Gangwar, B., 2001. Conservation of organic carbon in relation to crop productivity, yield stability and soil fertility under rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system. *Indian J. Agron.* 46, 1-4.

Krull, E.S., Skjemstad, J.O., Baldock, J.A., 2004. Functions of soil organic matter and the effect on soil properties. Grains Research and Development Corporation (GRDC).

Kundsen, D., Peterson, G.A., Pratt, P.F., 1982. Lithium, sodium and potassium. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), *Methods of Soil Analysis, Part 2*, 2nd Edition. Agronomy Monograph 9, ASA and SSSA, Madison, WI, pp. 225-246.

Kundu, S., Bhattacharyya, R., Prakash, V., Ghosh, B.N., Gupta, H.S., 2007. Carbon sequestration and relationship between carbon addition and storage under rainfed

soybean-wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil Till. Res.* 92, 87-95.

Lal, R., 1981. Soil erosion problems on alfisols in Western Nigeria, VI. Effects of erosion on experimental plots. *Geoderma* 25, 215-230.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623-1627.

Lal, R., 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degrad. Dev.* 17, 197-209.

Lal, R., 2009. Soils and food sufficiency. A review. *Agron. Sustain. Dev.* 29, 113-133.

Lal, R., 2010. Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. *Food Sec.* 2, 169-177.

Loveland, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. *Soil Till. Res.* 70, 1-18.

Lu, F., Wang, X., Han, B., Ouyang, Z., Duan, X., Zheng, H.U.A., Miao, H., 2009. Soil carbon sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's cropland. *Global Change Biol.* 15, 281-305.

Mahimairaja, S., Bolan, N.S., Hedley, M.J., Macgregor, A.N., 1994. Losses and transformation of nitrogen during composting of poultry manure with different amendments: An incubation experiment. *Bioresource Technol.* 47, 265-273.

Majumder, B., Mandal, B., Bandyopadhyay, P.K., Chaudhury, J., 2007. Soil organic carbon pools and productivity relationships for a 34 year old rice-wheat-jute agroecosystem under different fertilizer treatments. *Plant Soil* 297, 53-67.

Majumder, B., Mandal, B., Bandyopadhyay, P.K., Gangopadhyay, A., Mani, P.K., Kundu, A.L., Mazumdar, D., 2008. Organic Amendments Influence Soil Organic Carbon Pools and Rice-Wheat Productivity. *Soil Sci. Soc. Am. J.* 72, 775-785.

Manlay, R.J., Feller, C., Swift, M.J., 2007. Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. *Agr. Ecosyst. Environ.* 119, 217-233.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta.* 27, 31-36.

Oelofse, M., Markussen, B., Knudsen, L., Schelde, K., Olesen, J.E., Jensen, L.S., Bruun, S., 2015. Do soil organic carbon levels affect potential yields and nitrogen use efficiency? An analysis of winter wheat and spring barley field trials. *Eur. J. Agron.* 66, 62-73.

Olsen, R.J., Hensler, R.F., Attoe, O.J., 1970. Effect of manure application, aeration, and soil pH on soil nitrogen transformations and on certain soil test values¹. *Soil Sci. Soc. Am. J.* 34, 222-225.

Olsen, S.R., Cole, C.V., Watanabe, F.S. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate, Washington, USDA.

Page, A.L., Miller, R.H., (ed.), D.R.K., 1982. Methods of soil analysis. Part 2. Chemical and Microbiological Properties. Second Edition. *Agron. Monogr.* 9. ASA and SSSA, Madison, WI.

Pan, G.X., Smith, P., Pan, W.N., 2009. The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. *Agr. Ecosyst. Environ.* 129, 344-348.

Pan, G.X., Zhou, P., Zhang, X.H., Qiu, D.S., Chu, Q.H., 2006. Effect of different fertilization

- practices on crop carbon assimilation and soil carbon sequestration: a case study of a paddy under a long term fertilization trial from the Tai Lake region, China. *Acta Ecol. Sin.* 26, 3704-3710 (in Chinese with English summary).
- Patrick, M., Tenywa, J.S., Ebanyat, P., Tenywa, M.M., Mubiru, D.N., Basamba, T.A., Leip, A., 2013. Soil organic carbon thresholds and nitrogen management in tropical agroecosystems: concepts and prospects. *J. Sust. Dev.* 6, 31-43.
- Qin, Z.C., Huang, Y., Zhuang, Q.L., 2013. Soil organic carbon sequestration potential of cropland in China. *Global Biogeochem. Cy.* 27, 711-722.
- Rasmussen, P.E., Collins, H.P., 1991. Long-Term Impacts Of Tillage, Fertilizer, And Crop Residue On Soil Organic Matter In Temperate Semiarid Regions. In: Nyle, C.B. (Ed.), *Adv. Agron. Academic Press*, pp. 93-134.
- Rasmussen, P.E., Parton, W.J., 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. *Soil Sci. Soc. Am. J.* 58, 523-530.
- Seremesic, S., Milosev, D., Djalovic, I., Zeremski, T., Ninkov, J., 2011. Management of soil organic carbon in maintaining soil productivity and yield stability of winter wheat. *Plant Soil Environ.* 57, 216-221.
- Shi, R., 1976. Soil and agricultural chemistry analysis. (In Chinese.) China Agriculture Press, Beijing.
- Six, J., Feller, C., Denef, K., Ogle, S.M., de Moraes, J.C., Albrecht, A. 2002. Soil organic matter, biota and aggregation in temperate and tropical soils - Effects of no-tillage. *Agronomie.* 22: 755-775.
- Smith, P., 2004. Carbon sequestration in croplands: the potential in Europe and the global context. *Eur. J. Agron.* 20, 229-236.
- SPSS Inc. (1999). SPSS base 17.0 for Windows user's guide. SPSS Inc., Chicago IL.
- Srinivasarao, C., Venkateswarlu, B., Lal, R., Singh, A.K., Vittal, K.P.R., Kundu, S., Singh, S.R., Singh, S.P., 2012. Long-Term Effects of Soil Fertility Management on Carbon Sequestration in a Rice–Lentil Cropping System of the Indo-Gangetic Plains. *Soil Sci. Soc. Am. J.* 76, 168-178.
- SSSC (2000) Soil Science Society of China. Methods of soil agrochemistry analysis. Chinese Agriculture Science and Technology Press, Beijing, China (in Chinese)
- Sun, W., Huang, Y., Zhang, W., Yu, Y., 2010. Carbon sequestration and its potential in agricultural soils of China. *Global Biogeochem. Cy.* 24, GB3001.
- Tian, K., Zhao, Y., Xu, X., Hai, N., Huang, B., Deng, W., 2015. Effects of long-term fertilization and residue management on soil organic carbon changes in paddy soils of China: A meta-analysis. *Agriculture, Ecosystems & Environment* 204, 40-50.
- Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic matter in sustaining soil fertility. *Nature* 371, 783-785.
- Walkley, A., Black, I.A., 1934. An examination of the degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 37, 29-38.
- Wen, G., Winter, J.P., Voroney, R.P., Bates, T.E., 1997. Potassium availability with application of sewage sludge, and sludge and manure composts in field experiments. *Nutr. Cycl. Agroecosys.* 47, 233-241.
- Yan, X.Y., Gong, W., 2010. The role of chemical and organic fertilizers on yield, yield

- variability and carbon sequestration- results of a 19-year experiment. *Plant Soil* 331, 471-480.
- Yang, J., Gao, W., Ren, S., 2015. Long-term effects of combined application of chemical nitrogen with organic materials on crop yields, soil organic carbon and total nitrogen in fluvo-aquic soil. *Soil and Tillage Research* 151, 67-74.
- Yu, G.R., Fang, H.J., Gao, L.P., Zhang, W.J., 2006. Soil organic carbon budget and fertility variation of black soils in Northeast China. *Ecol. Res.* 21, 855-867.
- Zhang, W.J., Wang, X.J., Xu, M.G., Huang, S.M., Liu, H., Peng, C., 2010. Soil organic carbon dynamics under long-term fertilizations in arable land of northern China. *Biogeosciences* 7, 409-425.
- Zhang, W., Xu, M., Wang, B., Wang, X., 2009. Soil organic carbon, total nitrogen and grain yields under long-term fertilizations in the upland red soil of southern China. *Nutr Cycl Agroecosys* 84(1), 59-69.
- Zhang, X.B., Xu, M.G., Sun, N., Wang, X.J., Wu, L., Wang, B.R., Li, D.C., 2013. How do environmental factors and different fertilizer strategies affect soil CO₂ emission and carbon sequestration in the upland soils of southern China? *Appl. Soil Ecol.* 72, 109-118.
- Zhu, L., Li, J., Tao, B., Hu, N., 2015. Effect of different fertilization modes on soil organic carbon sequestration in paddy fields in South China: A meta-analysis. *Ecological Indicators* 53, 144-153.

Figure legends

Fig.1 Geographic locations of the long-term experimental sites. North East: Haerbin (HEB), Gongzhuling (GZL-A and -B), and Shenyang (SY); North West: Urumqi (UM), Zhangye (ZY), Pingliang (PL) and Yangling (YL); North: Changping (CP), Tianjin (TJ), Yucheng (YC), Zhengzhou (ZZ) and Xuzhou (XZ); South region: Suining (SN), Chongqing (CQ), Qiyang (QY) and Jinxian (JX).

Fig.2 Average yield variation (%) for wheat and maize for different treatments over the experimental period in each region. In a given region, treatments with a different letter (upper case for wheat or lowercase for maize) are significantly different at $P < 0.01$ as shown by LSD following one-way ANOVA. The error bar in each treatment is the standard deviation. CK is the unfertilized Control. N/A means that there was no NPS treatment in the North east, North and South region.

Fig.3 Annual C inputs from crop residues and manure/straw in different regions. In a given region, treatments with different lower case letter have a significantly different C input by crop biomass at $P < 0.01$ as shown by LSD following one-way ANOVA. Different uppercase letters show significant difference ($P < 0.01$) in total C input between the treatments. The error bar in each treatment is the standard deviation. Data for the NPS treatment sufficient for analysis were available only in the North West region.

Fig.4 Relationships between total cumulative C inputs and the increase in SOC stocks over the experimental period in different regions. n is the number of data points with data pooled from different fertilizer treatments and sites. Linear regression with groups indicated that slopes differed significantly between regions at $P < 0.01$.

Fig.5 Relationship between SOC stocks in the top 20 cm and relative yields of wheat (a) and maize (b) in different regions. n is the number of data points with data pooled from different fertilizer treatments, years and sites. The different symbols indicate the

different fertilizer treatments; relative yield of the NPK reference treatment was 1.0 (symbols not shown).

Fig.6 Relationship between SOC stocks in the 20 cm soil depth and yield variation of wheat and maize. Each value is the yield variation for a given fertilizer treatment at a site calculated over the experimental period and plotted against the average SOC stocks for the treatment over the same period.

**Effects of enhancing soil organic carbon sequestration in the topsoil by
fertilization on crop productivity and stability: evidence from long-term
experiments with wheat-maize cropping systems in China**

Xubo Zhang ^{1, 2}, Nan Sun ^{1*}, Lianhai Wu ², Minggang Xu ^{1*}, Ian J Bingham ³,
Zhongfang Li ⁴

¹ *Ministry of Agriculture Key Laboratory of Crop Nutrition and Fertilization, Institute
of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural
Sciences, Beijing 100081, China.*

² *Sustainable Soils and Grassland Systems Department, Rothamsted Research, North
Wyke, Okehampton, Devon EX20 2SB, UK.*

³ *Crop & Soil Systems Research, SRUC, Kings Buildings, West Mains Rd, Edinburgh
EH9 3JG, UK*

⁴ *Chemistry and Bioengineering College, Hezhou University, Hezhou 542899, China.*

* Corresponding author:
xuminggang@caas.cn , sunnan@caas.cn
Tel.: +86 10 82105636; FAX: +86 10 82106225;

Abstract

Although organic carbon sequestration in agricultural soils has been recommended as a ‘win-win strategy’ for mitigating climate change and ensuring food security, great uncertainty still remains in identifying the relationships between soil organic carbon (SOC) sequestration and crop productivity. Using data from 17 long-term experiments in China we determined the effects of fertilization strategies on SOC stocks at 0-20 cm depth in the North, North East, North West and South. The impacts of changes in topsoil SOC stocks on the yield and yield stability of winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) were determined. Results showed that application of inorganic fertilizers (NPK) plus animal manure over 20-30 years significantly increased SOC stocks to 20-cm depth by 32-87% whilst NPK plus wheat/maize straw application increased it by 26-38% compared to controls. The efficiency of SOC sequestration differed between regions with 7.4-13.1% of annual C input into the topsoil being retained as SOC over the study periods. In the northern regions, application of manure had little additional effect on yield compared to NPK over a wide range of topsoil SOC stocks (18 - >50 Mg C ha⁻¹). In the South, average yield from manure applied treatments was 2.5 times greater than that from NPK treatments. Moreover, the yield with NPK plus manure increased until SOC stocks (20-cm depth) increased to ~35 Mg C ha⁻¹. In the northern regions, yield stability was not increased by application of NPK plus manure compared to NPK, whereas in the South there was a significant improvement. We conclude that manure application and straw incorporation could potentially lead to SOC sequestration in topsoil in China,

42 but beneficial effects of this increase in SOC stocks to 20-cm depth on crop yield and
43 yield stability may only be achieved in the South.

44

45 **Keywords:** Soil organic carbon; yield; yield stability; manure application; straw
46 return; China

1. Introduction

Soil organic carbon (SOC) can play an important role in increasing crop productivity, improving soil fertility (Tiessen et al., 1994), reducing atmospheric carbon dioxide (CO₂) enrichment (Lal, 2004), and providing other ecosystem services, such as improved soil structure and water retention (Fan et al., 2013a). Low SOC stocks could reduce crop yield through effects on soil fertility and significant nutrient loss may also occur as a result of low nutrient buffer or retention capacity. Changes in SOC stocks have been reported extensively on the global (FAO, 2001), regional (Huang and Sun, 2006; Smith, 2004) and plot scales (Zhang et al., 2010), which suggests that society has paid increasing attention to the potential for sequestering organic carbon in soils in an effort to mitigate climate change and promote crop productivity. For example, it has been reported that a 1% increase in SOC content of the topsoil (0-20 cm) could increase cereal yield by 430 kg ha⁻¹ and reduce yield variability by 3.5% (Pan et al., 2009). However, others have argued that claims about the potential benefits of increasing C inputs to the soil must be made with caution because of the uncertainties regarding how much can be sequestered under different climates and soil types (Brock et al., 2011; Manlay et al., 2007; Seremesic et al., 2011). Therefore, it is imperative to quantify the relationships between C inputs, SOC sequestration and crop productivity.

In the last three decades, China has been facing a challenge to ensure crop production is increased while mitigating greenhouse gas (GHG) emissions. China uses only 7% of the world's arable land to feed 22% of the global population (Fan et al., 2010) and produces over 20% and 17% of the world's maize (*Zea mays* L.) and

wheat (*Triticum aestivum* L.) grain, respectively (FAO, 2010). If China intends to maintain the policy of grain self-sufficiency, crop productivity has to be increased without reducing soil fertility including SOC content, one of the indicators for ensuring crop production (D'Hose et al., 2014). Currently, the average SOC concentration in the root zone of croplands (about 10 g C kg⁻¹) in China is much lower than that (25-40 g C kg⁻¹) in Europe and the United States (Fan et al., 2010). Furthermore, SOC losses from China's croplands have been widely reported (Huang and Sun, 2006; Qin et al., 2013; Sun et al., 2010). SOC stocks of agro-ecosystems may be increased by improving agronomic practices. Applications of animal manure and the incorporation of straw in the soil are recognized as SOC-enhancing management options (Lu et al., 2009; Tian et al., 2015). It has been reported that SOC stocks in the top 20 cm of the world's soils increased by 0.24-0.46 Mg C ha⁻¹ yr⁻¹ with a decade of manure application (Gattinger et al., 2012). In addition, it was reported that in Southern China SOC in the topsoil (0-20 cm) increased by 3.8 Mg C ha⁻¹ following manure application for 22 years compared with soils receiving mineral fertilizers alone (Huang et al., 2010). It has also been estimated that an additional 3.8 Tg C yr⁻¹ could be sequestered in soil if all of the straw generated from arable fields in China were returned to the soils (Lu et al., 2009).

It is challenging to quantify the contribution of SOC to either maintaining or stabilizing crop yield, as the contribution could be concealed by other factors given the complex interactions that occur between soil, root systems and canopies (Bingham, 2001). Most studies conducted across the world have suggested that there is some

linear relationship between SOC stocks in the root zone and crop yield and its stability (Bauer and Black, 1994; Beyer et al., 1999; Lal, 2010; Smith, 2004). However, a significant non-linear relationship has been reported between relative crop yield and SOC in the root zone (Lal, 2009), which implies that there is an upper value of SOC stocks in the root zone beyond which there will be no additional benefit on crop yield of increasing SOC stocks (Loveland and Webb, 2003; Krull et al., 2004). For example, crop yields did not increase any further when SOC content in the topsoil exceeded 2 % in the upland soils of Alberta, Canada (Krull et al., 2004). Moreover there could be potential hazards of adding too much C to soils, such as surface crusting, increased detachment by raindrops, decreased hydraulic conductivity (Haynes and Naidu, 1998) and water-repellency (Olsen et al., 1970). Addition of excessive amounts organic materials to soils could also lead to losses in soil nitrogen (N) and/or phosphorus (P), resulting in surface and ground-water pollution (Patrick et al., 2013).

Determining the upper value of SOC stocks would provide guidance for designing management practices to optimise crop yields and mitigate climate change. However, there are few studies to date that have examined the relationship between SOC stocks and crop productivity, and quantified the maximal yield-responsive SOC stocks based on long-term observations (Lal, 2006; 2010). The objective of this research was to analyse datasets from 17 long-term fertilization experiments across China to: 1) determine the impact of different fertilizer application and straw management strategies on SOC sequestration in topsoil (0-20 cm) in different regions; 2) to establish the relationships between SOC stocks to 20-cm depth and crop yield

and yield stability for the different regions; and 3) to determine whether the maximal yield-responsive SOC stocks for enhancing cereal yields differs between regions. The overall aim of the research was to establish whether soil management practices to optimise yield and yield stability should be modified for specific regions.

2. Methods and materials

2.1 Long-term fertilization experiments

Datasets collected at 17 long-term fertilization experiments established between 1979 and 1990 in arable lands across China were used for this study (Fig. 1 and Table S1). Four sites were located in the North East region: Haerbin (HEB), Gongzhuling (GZL-A and -B), and Shenyang (SY); four in the North West region: Urumqi (UM), Zhangye (ZY), Pingliang (PL) and Yangling (YL); five in the North region: Changping (CP), Tianjin (TJ), Yucheng (YC), Zhengzhou (ZZ) and Xuzhou (XZ); and four in the South region: Suining (SN), Chongqing (CQ), Qiyang (QY) and Jinxian (JX).

Climatic conditions, and soil properties at the beginning of the experiments are presented in Tables S1 and S2. Various climatic types are represented in these regions. Annual average temperatures varied from 3.5 °C at the HEB site to 18.3 °C at the CQ site. Annual precipitation ranged from 127 mm at the ZY site (in the arid area) to 1581 mm at the JX site in the humid monsoon climate zone. Annual pan evaporation varied from 990 mm at the CQ site to 2570 mm at the UM site (data from China meteorological sharing service system, <http://cdc.cma.gov.cn/>). Annual evaporation at

the sites in the South region was almost the same as annual precipitation. However, it was much higher than annual precipitation in the other regions (Table S1). Irrigation was applied at the majority of sites in the North and North West (Table S1).

2.2 Management of the field experiments

A detailed description of the cropping systems is shown in Table 1. A monoculture cropping system was practiced at the GZL-A and -B, SY, and PL sites with continuous maize, while a rotation of winter wheat-winter wheat-maize (i.e., two wheat seasons followed by a maize season) at the ZY and UM sites. However, the rotation at site ZY changed once between 1994 and 1997, i.e., three continuous wheat seasons followed by one maize season. A double cropping system was practiced at the other sites; at JX it was maize-maize, at SN and CQ it was wheat-rice (*Oryza sativa* L.), whilst at the remaining sites it was summer maize-winter wheat. At all sites, weeds were removed manually and pesticides were applied when needed to control insect pests and fungal diseases.

Four types of treatments common among all sites were chosen for this study: (i) unfertilized (thereafter, Control); (ii) inorganic N, P and/or potassium (K) fertilizer combined (hereafter referred to as, NP and NPK); (iii) inorganic NP and NPK plus wheat or maize straw returned (hereafter, NPS and NPKS); and (iv) inorganic NP and NPK plus animal manure (hereafter, NPM and NPKM) or 1.5-2.0 times amount of N in manure only or of total N application (hereafter, hNPKM) used in the NPKM treatment. The application rate of inorganic N (urea), P and K fertilizer that could ensure high crop yield at a particular site was set according to recommended rates for

commercial crops in the regions (NP and NPK; Table 1). The inorganic N, P and K fertilizers were applied five to seven days before sowing. The fertilizer-N strategy in the NPM and NPKM treatment differed between sites. At HEB, GZL-B, SY, CP, YC, XZ, ZY, PL, SN, CQ and JX sites the same amount of inorganic N was applied as in the NP and NPK treatments, thus, at these sites the NPM and NPKM treatments received additional N from manure. At GZL-A, TJ, ZZ, UM, YL and QY, the same amount of total N was applied to NP/NPK and NPM/NPKM treatments at a given site, with 30-50% of it from inorganic N-fertilizer when manure was added (i.e., NPM/NPKM). For the NPS and NPKS treatments, maize and wheat straw was chopped and incorporated into the soil (0-20 cm depth) immediately after harvest. N content in straw, was deducted from the total amount of fertilizer-N applied at GZL-A and UM (1995 onwards) so that the total N applied was the same as that received by NP and NPK treatments at these sites. At remaining sites no deduction was made, because the information on N content in straw could not be provided in time for when fertilizers were applied. Micronutrient fertilizers containing boron, zinc, manganese, magnesium and iron were applied across all treatments at the QY site every two to four years to avoid potential deficiencies.

The treatments with large plots ($>100\text{m}^2$, Table S3) did not have replicates except those at the SY, PL, and QY sites. Otherwise, the treatments had two to four replicates (Table S3). At all sites, 100cm depth cement baffle plates were erected along the boundaries of each plot to avoid lateral exchange of water and nutrients between adjacent plots. The treatments were initially randomized at each site and then that

treatment was fixed to the plot in the following years.

2.3 Soil and Plant Sampling and Analysis

Soil samples were collected from the top 20cm soil depth at the beginning of the experiments, and then annually from each plot approximately 15 d after harvest. As the plough depth ranged from 20-25 cm across sites and regions, the depth of soil sampling represents the minimum plough depth for the study. Twenty cores from each plot were collected randomly using a soil auger (5 cm diameter) and the soil from a random four cores combined, which formed five samples for each plot. Air-dried soils (~20 kg, 7 d) were sieved through a 2 mm screen to determine pH (1:1 w/v water) and other soil properties. Sub-samples were crushed to 0.25mm for the measurements of SOC, total N (TN), total P (TP), and total K (TK). SOC content was determined by sulphuric acid-potassium dichromate oxidation (Walkley and Black, 1934). TN was determined by the method described by Bremner and Mulvaney (1965), TP by Murphy and Riley (1962), and TK by Kundsén et al. (1982). Available N was measured following the method of Jackson (1958). Available P was determined by the Olsen-P method (Olsen et al., 1954) and available K by the method of Shi (1976). The contents of TN, TP, and TK in manure were measured following the procedures described by Mahimairaja et al. (1994), Barnett (1994), and Wen et al. (1997), respectively. Soil bulk density was measured by using steel ring with 5-cm diameter, and soil samples were taken at 10 cm depth, dried at 105 °C for eight hours and then weighed (SSSC 2000).

Maize and wheat plants were harvested manually close to the ground with sickles

and all harvested materials were removed from the plots for all the treatments except the NPS and NPKS treatments. Thus, only roots and shed leaf litter were left on the plots. The harvested plants were air-dried, threshed, and oven-dried at 70°C to constant dry weight. For each treatment plot, five samples from the dried straw and grains each were collected for the measurement of nutrient contents. Sampled dry matter was digested with H₂SO₄-H₂O₂, and the concentrations of TN, TP and TK in the digesting solution were measured using the micro-Kjeldahl method, colorimetric analysis and dissolution-flame photometry, respectively (Page et al., 1982). For the NPS and NPKS treatments, the crop residues were chopped and incorporated into the soils (0-20 cm) by disking immediately after harvest each year. Grain yield from a plot was determined from each whole plot.

2.4 Carbon inputs from crops

It was assumed that the annual biomass input from roots, exudation and dead materials by wheat and maize is 30% of aboveground dry matter (Kundu et al., 2007; Zhang et al., 2010), and that 75 and 85% of the total root biomass was in the surface 20 cm of the soils for wheat and maize, respectively (Jiang et al., 2014). 39.9 and 44.4 g C kg⁻¹ (dry matter), as a national average (NCATS, 1994), were used to represent the C contents in dry matter for wheat and maize, respectively. For the NPKS treatment, C contents in maize and wheat straw were set to 12.4 and 27.8 g C kg⁻¹ (fresh weight), respectively (Zhang et al., 2010).

2.5 Statistical analysis

SOC concentration (SOC_C) in the top 20 cm of the soil was converted to SOC stock (SOC_S , Mg C ha⁻¹):

$$SOC_S = SOC_C \times d \times BD \times 10 \quad (1)$$

where d is the soil depth (0.2 m), BD is the soil bulk density (g cm⁻³) and 10 is a unit conversion factor.

SOC_S in a given year can also be expressed as a function of the number of the years since an experiment started (Y_n):

$$SOC_S = aY_n + b \quad (2)$$

where a represents the rate of change in SOC stocks (Mg C ha⁻¹ yr⁻¹) in the top 20 cm depth and b is the SOC stocks at the beginning of the experiment. A similar expression was applied to crop yield (Y_{grain}). However, the slope a represents the rate of change (kg ha⁻¹ yr⁻¹) of crop yields and the intercept b is the initial crop yield. Linear regression was used to fit these functions and the residuals examined to determine the suitability of a linear model. There was no evidence of non-linearity for any of the sites.

As the dataset from long-term experiments in different regions or cropping systems cannot be compared directly, relative crop yield (YR) was used to minimise the influences of crop variety replacement, seasonal variation in weather conditions and changes in agronomic practices during the study period and to make the dataset from individual experiments more comparable. YR was calculated based on the annual

data from the long-term experiments across the four regions.

$$YR = \frac{YE}{Y_{NPK}} \quad (3)$$

where YE is the actual yield of either wheat or maize from a treatment (kg ha^{-1}) at a given site in a given year and Y_{NPK} is the yield of the crop from the NPK treatment at the same site in the same year.

To obtain the maximal yield-responsive SOC_s (SOC_{opt}) for relative crop yield, the linear-plateau model was chosen to quantify the relationship between YR and SOC_s in a given year (Bai et al., 2013; Lal, 2010):

$$YR = \begin{cases} A \cdot SOC_s + B & (SOC_s < SOC_{opt}) \\ YP_{max} & (SOC_s \geq SOC_{opt}) \end{cases} \quad (4)$$

where A means that the relative yield increment per 1 Mg C ha^{-1} SOC increment and B is the relative yield at the initial SOC level in an experiment site; SOC_{opt} (Mg C ha^{-1}) is the upper value of SOC beyond which there is no additional benefit for relative crop yield of increasing SOC stocks further; YP_{max} is the predicted plateau maximum relative yield and fitted with the data. Models were fitted using Genstat (version 16th Edition, 2013, VSN international Trust, Hemel Hempstead, UK).

The stability of grain yield for a treatment was evaluated by its variability (CV , %) (Pan et al., 2009):

$$CV = \frac{Y_{std}}{Y_m} \times 100 \quad (5)$$

where Y_{std} is the standard deviation of the yields of a particular treatment at a site over

the whole experimental period and Y_m is the mean yield for the treatment within the same period. Differences between regions were then compared using values of CV averaged across sites within regions.

The exponential decay equation was used to characterize the relationship between the average SOC_s under a given treatment and yield variation during the experimental period:

$$CV = \beta_0 + \beta_1 e^{-\beta_2 SOC_s} \quad (6)$$

where β_0 is the lower value of CV (lower value of asymptotic line), $\beta_0 + \beta_1$ is the maximum value of CV and β_2 is the rate of decrease of CV.

One-way ANOVA was applied to test the significance of the effects of fertilizer treatments on the average relative yields and SOC storage within the regions. Differences between specific treatments within a region were compared with the least significant differences (L.S.D) at either the 5% or 1% level of probability depending on the analysis. Simple linear regression with groups (Genstat version 16th Edition, 2013, VSN international Trust, Hemel Hempstead, UK) was used to compare the slopes of the relationships between total cumulative C input and the increase in SOC storage between regions. With the exception of fitting linear-plateau models and linear regression with groups (above), all statistical analyses were performed with SPSS v. 17.0 for Windows (SPSS, Inc., 1999, Chicago, USA, www.spss.com). Prior to analysis residuals were checked for homogeneity of variance and normality to ensure that they satisfied the assumptions of parametric tests.

3. Results

3.1 Crop yield and stability

The mean annual rates of change in crop yields over time under the different fertilization strategies at each site are shown in Table 2. At all sites but SY (where there was an increase) crop yield in the control (unfertilized) treatment either did not change or decreased on average over time. The trends for the other treatments were more variable with both positive and negative changes in mean annual yields over the study periods. For application of NPK fertilizer, 37% of the site-crop combinations showed a positive yield trend, whilst 22% showed a negative yield trend. When manure was applied this proportion was 51% (NPKM) and 67% (hNPKM) of site-crops with positive yield trends and only 11 and 6%, respectively, with negative trends.

When averaged over the experimental period, the yields of wheat relative to the NPK treatment showed a similar pattern in all the regions (Table 3). The highest relative yields were in the manure applied treatments, followed by NPKS. The relative yields were significantly ($P < 0.05$ LSD) greater than the NPK reference in the North West and South, but not the North East and the North indicating that in two out of four regions there was a yield response to application of manure over and above that observed with inorganic NPK. Addition of manure resulted in an improvement in relative yields compared to straw (NPKS) only in the North and South. Yields for the NP treatment were marginally lower than those of the NPK reference in the northern

sites (6-12%; $P < 0.05$ for the North and North West) indicating only a small increase in yield in response to application of K fertilizer. However, the response was greater (12% $P < 0.05$) in the South. Unfertilized controls had yields lower than those for the other treatments.

The relative yields of maize responded in a similar way to fertilizer treatment as those for wheat. By far the greatest benefits to yield from manure additions were found in the South. Smaller ($P < 0.05$) benefits over NPK were found in the North East and North West. The beneficial effects on yield of returning straw to the soil were observed only in the South (Table 3).

Annual yield variation (CV %) was around 20 to 30% for wheat and maize in the North East region, and did not differ between treatments (Fig. 2). In unfertilized controls wheat and maize yield variability in the North and North West was greater (CV approximately 35%) than in the North East ($P < 0.05$), and declined ($P < 0.05$) with the addition of inorganic fertilizer and manure. Thus, the average yield variability of the NPM, NPKM and hNPKM treatments was less (yield was more stable) than that of the control treatment in the North and North West. In the South, yield variability was considerably greater (CV $> 60\%$) than in the northern regions when no fertilizer was applied. Moreover application of NP and NPK did not reduce this variability unlike the response in the northern regions. Applications of manure (NPM, NPKM, hNPKM) reduced yield variability to values comparable to the other regions (CV $\sim 20\%$). By contrast, straw incorporation (NPS, NPKS) did not cause a reduction in yield variability to the same extent as manure.

3.2 Topsoil SOC stocks and C inputs

In order to compare the effects of fertilizer treatments on SOC stocks (i.e. contents), SOC at beginning and end of the experimental period in different regions were compared (Table 4). Average SOC stocks for the Control treatment at the beginning of experiments was the lowest among the treatments in all the regions (19.3-31.9 Mg C ha⁻¹) and the value decreased in the North West and North regions over the whole experimental period, but not in the North East and South. The inorganic fertilizer treatments NP and NPK had relatively small effects on SOC stocks over the experimental period in the North East region. In the other regions, however, SOC stocks in the NP and NPK treatments increased ($P<0.05$). By contrast addition of manure (NPM, NPKM and hNPKM) led to an increase ($P<0.05$) in SOC relative to controls and inorganic fertilizer treatments in all regions ($P<0.05$). Averaged across manure treatments the increases in SOC from beginning to end of experiments were 18, 43, 14 and 23% in the North East, the North West, the North and the South region, respectively. The average SOC stocks from the NPKS treatment at the end of experiments were higher ($P<0.05$) than that at the beginning of the experiments in all the regions. Moreover, the increases in SOC stocks were smaller following straw incorporation than following addition of manure in all regions.

Regional averages of SOC stocks mask considerable variation in SOC dynamics between individual sites. The rates of change in SOC stocks to 20-cm depth under different fertilization strategies at each site are shown in Table 5. With the exception of the CP, YC and YL sites there was either no change (9 sites) or a decrease (5 sites)

in SOC stocks over time in the unfertilized Control treatment. With NPK there was an increase (5 sites), no change (10 sites) or a decrease (1 site) over 20 to 30 years. By contrast, manure application and straw incorporation resulted in an increase ($P<0.05$) of 0.18-1.38 and 0.18-0.62 Mg C ha⁻¹ yr⁻¹ respectively at over 80% of the monitored sites. Further, at sites where there was an increase in SOC stocks over time without fertilizer, the rate of increase with additions of manure and straw were approximately 2 to 7 fold greater.

Average annual C inputs from crops and manure for different treatments in all four regions are shown in Fig. 3. Input of C from crops where only inorganic fertilizer was applied (NP and NPK) was approximately double that of the Control treatment in each of the regions. Furthermore, there were no differences in annual C input from crops between the inorganic fertilizer, manure application and straw incorporation treatments. Total C input to the soil was greater where manure was applied and straw returned to the soil compared with plots receiving inorganic fertilizer only.

In addition, positive linear relationships between change rate of SOC stocks and annual C inputs to the soils over the experimental period were found (Fig. 4). The slopes for the regions ranged from 0.074 to 0.131 which indicated that 7.4% to 13.1% of the annual C inputs could be sequestered in the soils. The slopes differed significantly ($P<0.05$) between regions, with the retention rate of C inputs in the North West being greater than that in the South and North East.

3.3 Responses of crop yield and yield stability to changes in topsoil SOC stocks

Data from individual treatments and sites within a region were combined to examine

the relationship between SOC stocks and relative yield. Significant correlations between SOC stocks and relative yield were found with an apparent maximal yield-responsive SOC stock (SOC_{opt}) above which there may be no increase in relative yield (Fig. 5). YR_{max} determined with the linear-plateau model ranged from 1.14 to 1.43 for wheat and from 1.13 to 2.06 for maize. The greatest relative yields were observed in the South region. The corresponding values of SOC_{opt} were 46.2, 26.5, 21.8 and 34.7 Mg C ha⁻¹ for wheat and 44.4, 28.0, 22.0 and 34.8 Mg C ha⁻¹ for maize in the North East, the North West, the North and the South region, respectively.

Relationships between the variability of wheat and maize yields and the average SOC stocks over experimental period are shown in Fig. 6. There was no correlation in the North East region. However, in the other three regions, with the increase in SOC stocks, the yield variability for both wheat and maize showed a relatively weak (r^2 0.38-0.59) exponential decrease, i.e. yield stability increased with increases in topsoil SOC stocks.

4. Discussion

4.1 Impact of fertilization management on topsoil SOC stocks

Whether or not organic C can be retained in soils depends on the balance between C input and output as influenced by agronomic practices (e.g., fertilization, straw return, rotation, tillage, etc.) and climatic conditions. Results from the present study show that N fertilizer application and organic soil amendments influenced the rate of C sequestration, and that rates differed between regions and sites within regions because of differences in soil type, management and climate which can impact on the retention

of SOC in soils (Gabriel and Kellman, 2011; Gattinger et al., 2012; Lu et al., 2009; Six et al., 2002). Balanced application of inorganic N, P, and K fertilizers increased SOC stocks at four out of five sites in the North, but at only one site in the North West and none in the North East and South regions. The annual rates of change of SOC to 20-cm depth for the regions were broadly consistent with those reported by Lu et al. (2009) when compared at similar application rates of N. By contrast, straw incorporation and application of animal manure led to more consistent increases in SOC stocks at the 20-cm soil depth across sites and regions, with the average rate from manure application ($0.67 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) being over twice that from straw incorporation ($0.29 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) for sites where both treatments were included (Table 5).

The slope of the linear relationship between SOC increment and cumulative C input to soils can be considered as the proportion of total C input that is retained in the soils, which ranged from 7.4 to 13.1% between regions. In fact, for a given treatment, estimated annual C inputs differed relatively little between regions (Fig. 3). Moreover, there was only a weak association between the average initial soil C stock of a region and its C retention rate ($P = 0.19$, $R^2 = 0.48$ data not shown), suggesting that the observed differences in retention rate between regions were largely the result of differences in climate or soil properties rather than the initial topsoil SOC stocks. The range of sequestration efficiencies was similar to that observed from the Indian humid subtropical plains at 20-cm depth under a rice-wheat over 20-30 years (7.6-14%, Majumder et al., 2008) and a rice-lentil (*Lens culinaris*) system (9.9%, Srinivasarao et

al., 2012), but lower than that from the temperate region of North America (14-21%, Rasmussen and Collins, 1991) and higher than that from topsoil of subtropical regions under a rice-wheat-jute (*Corchorus olitorius L.*) system (4-5%, Majumder et al., 2007).

4.2 Relative yield response to enhancement of SOC stocks

Investigating the effects of SOC stocks *per se* on yield is difficult, because treatments designed to vary SOC stocks, such as the addition of organic matter, also alter the supply of nutrients alongside effects on soil structure and water holding capacity etc. (Bauer and Black, 1994; Johnston et al., 2009; D'Hose et al., 2014; Loveland and Webb, 2003; Oelofse et al., 2015). Moreover, analysis of relationships using long-term data sets are subject to large variation in yield arising from seasonal variation in weather conditions and changes in agronomic practices during the study period such as the crop rotation. We have minimised these sources of variation by expressing the yield observed under a specific treatment relative to the yield obtained in the same year and site with a full balanced (NPK) inorganic fertilizer supply. When data from the different fertilizer treatments and sites within a region were combined and relative yields plotted against topsoil SOC stocks, apparent maximal yield-responsive SOC stocks (SOC_{opt}) were obtained comparable to that reported by Krull et al. (2004) in a reworking of total biomass yields from sites in arable land of Canada.

In the present study SOC_{opt} values were derived from the fitting of a linear-plateau model to all data including those from unfertilized controls, and thus,

interpretation of the agronomic significance of the SOC_{opt} must be made cautiously.
 The large increase in relative yield from values <1.0 to 1.0 is obtained over a narrow
 range of topsoil SOC stocks in each region and is associated with the application of
 NP and NPK fertilizer. These increases in yield can, therefore, be ascribed to the
 nutritional benefits of fertilizer supply (Oelofse et al., 2015; Pan et al., 2009). In the
 North, and North West, there was a small increase (4-15%) in average relative yield of
 wheat and maize with applications of manure (NPKM and hNPKM, Table 3), which
 was similar to the results reported by Beyer et al., (1999). As the rates of NPK applied
 were based on the recommended fertilizer rates required to satisfy the nutrient
 requirements of commercial crops in the region, the results suggest that manure
 applications may have had small beneficial effects on yield through the supply of
 other macronutrients in the northern regions such as S, micronutrients, or via effects
 on soil physical or biological properties (Zhang et al., 2010). Importantly, the effects
 appeared to occur independently of topsoil SOC stocks over a wide range from
 approximately 18 to >50 Mg C ha⁻¹ (0.72 – >2.0%). In this regard, when the effects of
 NPK supply are taken into account (i.e., when crops are supplied with inorganic NPK
 fertilizer) there appears to be no clear maximal yield-responsive topsoil SOC stocks
 for sustaining the yield of wheat and maize in the North and North West. It was
 reported that wheat and maize yields in plots supplied with animal manure did not
 differ from those given inorganic NPK for 33 years in the North of China (Yang et al.,
 2015). A similar interpretation can be made for the North East even though the
 linear-plateau model yielded a high apparent SOC_{opt} . The high SOC_{opt} results from the

greater variation in the data for this region, especially for unfertilized Controls, and lower coefficient of determination ($R^2 \leq 0.35$).

The concept of maximal yield-responsive SOC stocks has been proposed previously (Loveland and Webb, 2003; Krull et al., 2004), but it has been argued that the quantitative evidence for such an upper value(s) is weak, at least for soils in temperate climates (Loveland and Webb, 2003; Oelofse et al., 2015). Our data for the temperate regions of China support this view. It is worth emphasising too that the range of SOC concentrations (from 0.5% to 1.9%) measured in our soils was well below the threshold of 2% (to 0-20 cm soil depth) generally believed to be critical for maintaining soil functions (Loveland and Webb, 2003). However, our data also indicated that the response in the sub-tropical climate of the South region is appreciably different to the northern regions. In the South there was a marked increase in yield of both wheat and maize with application of manure plus inorganic NPK relative to inorganic NPK on its own (Table 3). Moreover, the relative yield increased with NPKM treatment as SOC stocks increased up to the SOC_{opt} of 35 Mg C ha⁻¹ (Fig. 5). It is conceivable that in the climate, soils and production systems of the South there is a more marked deficiency in the supply of nutrients other than NPK compared to the northern regions and that supply of animal manures and straw, or higher SOC concentrations are required to satisfy these requirements (Zhang et al., 2009, 2010). Alternatively, the restriction to yield may be from some aspect of soil physical quality associated with low SOC stocks (<35 t C ha⁻¹, 1.39 % dry weight) such as soil structure, drainage or soil water retention (Fan et al., 2013a) and that this is alleviated

as SOC is increased by addition of manure.

It can be estimated that the yields of wheat and maize crops in the South region could be increased by 89.6 and 252.4 kg ha⁻¹ respectively for each 1.0 Mg C ha⁻¹ increment in topsoil SOC up to SOC_{opt} . These rates are considerably higher than the 10 – 43 kg ha⁻¹ reported for cereal production in other areas of the world (Lal, 1981; Bauer and Black, 1994; Diaz-Zorita et al., 2002; Pan et al., 2009). Thus, based on average regional yields of wheat (3.1 Mg ha⁻¹) and maize (4.4 Mg ha⁻¹) in the south of China (National Bureau of Statistics of China, 2009), the yield of wheat could be increased by 1.94 and maize by 3.04 Mg ha⁻¹ if SOC stocks was increased to its SOC_{opt} . An additional 198 Mg C ha⁻¹ would need to be retained in soils in the south of China in order to fill the gap between current stock levels and SOC_{opt} . If SOC_{opt} is to be reached in the next 30 years at least 6.6 Mg C ha⁻¹ yr⁻¹ should be applied to the soil (most effectively as animal manure) given that 9% of the C input is sequestered (Fig. 4).

4.3 Yield stability vs. topsoil SOC stocks

Yield stability is an important indicator of agricultural sustainability (Katyal et al., 2001; Lal, 2004; Seremesic et al., 2011). Whether increasing SOC stocks can reduce yield variation is still a matter of debate (Pan et al., 2009; Pan et al., 2006; Yan and Gong, 2010). There is evidence that yield variability increases when crop growth and yield become more dependent on soil fertility to supply the required mineral nutrients (e.g. with zero or unbalanced inorganic fertilizer applications) (Yan and Gong, 2010).

Our data suggest that the extent to which this occurs may depend on the range of SOC stocks or other regional differences in soil and/or climatic conditions. Thus, in the North East there was little difference in the variability of wheat and maize yields between any of the fertilizer treatments (Fig. 2), even though the actual yield of unfertilized Controls was generally ~50-60% of that of crops receiving NPK (Table 3, Fig. 5). This implies that yields of unfertilized crops, although lower, were not more susceptible to seasonal variation in other abiotic and biotic stresses than fertilized crops. Furthermore, variation of wheat and maize yield did not show any clear trend, this may be because of beneficial effects of the high SOC stocks in soils in this region (30 - 45 Mg C ha⁻¹ average for the experimental period, Fig. 6) increasing crop resilience to biotic and abiotic stresses (Fan et al. 2013b), or an inherently lower seasonal variation in climatic conditions or pest problems in this region compared to others. In the North, North West and South, significant negative exponential relationships were found between topsoil SOC stocks and yield variation (Fig. 6). For the North and North West much of the reduction in variability (increase in stability) was associated with the supply of balanced NPK fertilizer (Fig. 2); there was relatively little further improvement with additions of animal manure and increases in SOC stocks above 18 and 25 Mg C ha⁻¹ for the North and North West, respectively. In the South, however, balanced fertilizer applications alone did not substantially reduce yield variability of either wheat or maize and, unlike the northern regions, there may be appreciable benefits for stabilizing yield of applying manure to raise the topsoil SOC stocks above 30 Mg C ha⁻¹.

5. Conclusions

This study shows that whilst there is significant potential for sequestering C in topsoil across several regions of China through straw incorporation and application of animal manure along with NPK fertilizer, there are strong regional differences in the benefits of SOC stocks on the yield and yield stability of wheat and maize. We estimate that if the same amount of manure and straw used in the experiments were applied to the soils in the wheat and maize planted areas, 22.7 and 12.9 Tg C yr⁻¹ respectively could be sequestered in the soils of the four regions studied. Moreover, there was no evidence of the soils reaching saturation. However, in the North, North East and North West, use of animal manure or straw to increase topsoil SOC stocks above current values had relatively little benefit for yield and yield stability relative to the application of NPK fertilizer. In the South, there were substantial yield responses to applications of manure over and above those obtained with NPK and hence there is potential for increasing yield, and improving yield stability, by using manure to increase topsoil SOC stocks to the SOC_{opt} of 35 Mg C ha⁻¹. This could make a significant contribution to improving agricultural sustainability in the region.

Acknowledgements

Financial support was from National Basic Research Program (2011CB100501), National Key Technologies R&D Program (2012BAD14B04), National Science Foundation of China (41171239) and Natural Science Foundation of China (41371247). The authors acknowledge all colleagues from the long-term fertilization

experimental sites for their unremitting assistance. The authors also thank two anonymous reviewers for their constructive comments on an earlier version of this paper.

References

- Bai, Z., Li, H., Yang, X., Zhou, B., Shi, X., Wang, B., Shen, J., Chen Q., Qin, W., Oenema, O., Zhang, F. 2013. The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. *Plant soil*, 372: 27-37.
- Barnett, G.M., 1994. Phosphorus Forms in Animal Manure. *Bioresource Technol.* 49, 139-147.
- Bauer, A., Black, A.L., 1994. Quantification of the effect of soil organic-matter content on soil productivity. *Soil Sci. Soc. Am. J.* 58, 185-193.
- Beyer, L., Sieling, K., Pingpank, K., 1999. The impact of a low humus level in arable soils on microbial properties, soil organic matter quality and crop yield. *Biol. Fert. Soils* 28, 156-161.
- Bingham, I.J., 2001. Soil-root-canopy interactions. *Annals of Applied Biology* 138, 243-251.
- Bremner, J.M., Mulvaney, C.S., 1965. Nitrogen-Total. In: *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties* (ed. Black, CA), pp. 595-624, Am. Soc. Agron., Madison.
- Brock, C., Fliessbach, A., Oberholzer, H.R., Schulz, F., Wiesinger, K., Reinicke, F., Koch, W., Pallutt, B., Dittman, B., Zimmer, J., Hulsbergen, K.J., Leithold, G., 2011. Relation between soil organic matter and yield levels of nonlegume crops in organic and conventional farming systems. *J. Plant Nutr. Soil Sci.* 174, 568-575.
- Cotching, W.E., Hawkins, K., Sparrow, L.A., McCorkell, B.E., Rowley, W., 2002. Crop yields and soil properties on eroded slopes of red ferrosols in north-west Tasmania. *Aust. J. Soil Res.* 40, 625-642.
- D'Hose, T., Cougnon, M., De Vlieghe, A., Vandecasteele, B., Viaene, N., Cornelis, W., Van Bockstaele, E., Reheul, D., 2014. The positive relationship between soil quality and crop production: A case study on the effect of farm compost application. *Appl. Soil Ecol.* 75, 189-198.
- Díaz-Zorita, M., Duarte, G.A., Grove, J.H., 2002. A review of no-till systems and soil management for sustainable crop production in the subhumid and semiarid Pampas of Argentina. *Soil Till. Res.* 65, 1-18.
- Fan, M., Cao, J., Wei, W., Zhang, F., Su, Y., 2013a. Managing soil organic carbon for advancing food security and strengthening ecosystem services in China. In: *Ecosystem services and carbon sequestration in the biosphere.* (eds Lal R, Lorenz K, Hüttl RF, Schneider BU, Von Braun J), pp. 419-429, Springer Netherlands.
- Fan, M., Christie, P., Zhang, W., Zhang, F., 2010. Crop production, fertilizer use and soil quality in China. In: *Advanced in Soil Science: Food security and soil quality.* (eds Lal

R, Stewart BA), pp. 87-108, CRC Press, , London, New York.

Fan, M., Lal, R., Cao, J., Qiao, L., Su, Y., 2013b. Plant-Based assessment of inherent soil productivity and contributions to China's cereal crop yield increase since 1980. *Plos One* 8, e74617 doi:74610.71371/journal.pone.0074617.

FAO, 2001. Soil carbon sequestration for improved land management. World Soil Resources Reports, 2001, No 96, Food & Agric. Organization, Rome, Italy, ISSN, 0532-0488.

FAO, 2010. FAOSTAT Database - Agriculture Production. Rome: Food and Agriculture Organization of the United Nations.

Gabriel, C.E., Kellman, L. 2011. Examining moisture and temperature sensitivity of soil organic matter decomposition in a temperate coniferous forest soil. *Biogeosciences Discussion*. 8:1369-1409.

Farquharson, R.J., Schwenke, G.D., Mullen, J.D., 2003. Should we manage soil organic carbon in Vertosols in the northern grains region of Australia? *Aust. J..Exp. Agr.* 43, 261-270.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mader, P., Stolze, M., Smith, P., Scialabba, N.E.H., Niggli, U., 2012. Enhanced top soil carbon stocks under organic farming. *P. Natl. Acad. Sci. USA*. 109, 18226-18231.

GenStat 16th Edition, 2013. Service Pack 1 Version 16.2.0.11713. VSN international Trust, Hemel Hempstead, UK.

Haynes, R.J., Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutr. Cycl. Agroecosys*. 51, 123-137.

Huang, S., Peng, X., Huang, Q., Zhang, W., 2010. Soil aggregation and organic carbon fractions affected by long-term fertilization in a red soil of subtropical China. *Geoderma*, 154, 364-369.

Huang, Y., Sun, W.J., 2006. Changes in topsoil organic carbon of croplands in mainland China over the last two decades. *Chinese Sci. Bull.* 51, 1785-1803.

Jackson, M. L., 1958. Soil chemical analysis. pp. 183-204, Prentice-Hall, Inc. New York..

Johnston, A.E., Poulton, P.R., Coleman, K., 2009. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *Adv. Agron.* 101, 1-57.

Jiang, G., Xu, M., He, X., Zhang, W., Huang, S., Yang, X., Liu, H., Peng, C., Shirato, Y., Iizumi, T., Wang, J., Murphy, D.V., 2014. Soil organic carbon sequestration in upland soils of northern China under variable fertilizer management and climate change scenarios. *Global Biogeochem. Cy.*, 2013GB004746.

Katyal, V., Gangwar, K.S., Gangwar, B., 2001. Conservation of organic carbon in relation to crop productivity, yield stability and soil fertility under rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system. *Indian J. Agron.* 46, 1-4.

Krull, E.S., Skjemstad, J.O., Baldock, J.A., 2004. Functions of soil organic matter and the effect on soil properties. Grains Research and Development Corporation (GRDC).

Kundsen, D., Peterson, G.A., Pratt, P.F., 1982. Lithium, sodium and potassium. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), *Methods of Soil Analysis, Part 2*, 2nd Edition. Agronomy Monograph 9, ASA and SSSA, Madison, WI, pp. 225-246.

Kundu, S., Bhattacharyya, R., Prakash, V., Ghosh, B.N., Gupta, H.S., 2007. Carbon sequestration and relationship between carbon addition and storage under rainfed

629 soybean-wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil Till. Res.* 92,
630 87-95.

631 Lal, R., 1981. Soil erosion problems on alfisols in Western Nigeria, VI. Effects of erosion on
632 experimental plots. *Geoderma* 25, 215-230.

633 Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security.
634 *Science* 304, 1623-1627.

635 Lal, R., 2006. Enhancing crop yields in the developing countries through restoration of the
636 soil organic carbon pool in agricultural lands. *Land Degrad. Dev.* 17, 197-209.

637 Lal, R., 2009. Soils and food sufficiency. A review. *Agron. Sustain. Dev.* 29, 113-133.

638 Lal, R., 2010. Beyond Copenhagen: mitigating climate change and achieving food security
639 through soil carbon sequestration. *Food Sec.* 2, 169-177.

640 Loveland, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils
641 of temperate regions: a review. *Soil Till. Res.* 70, 1-18.

642 Lu, F., Wang, X., Han, B., Ouyang, Z., Duan, X., Zheng, H.U.A., Miao, H., 2009. Soil carbon
643 sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's
644 cropland. *Global Change Biol.* 15, 281-305.

645 Mahimairaja, S., Bolan, N.S., Hedley, M.J., Macgregor, A.N., 1994. Losses and
646 transformation of nitrogen during composting of poultry manure with different
647 amendments: An incubation experiment. *Bioresource Technol.* 47, 265-273.

648 Majumder, B., Mandal, B., Bandyopadhyay, P.K., Chaudhury, J., 2007. Soil organic carbon
649 pools and productivity relationships for a 34 year old rice–wheat–jute agroecosystem
650 under different fertilizer treatments. *Plant Soil* 297, 53-67.

651 Majumder, B., Mandal, B., Bandyopadhyay, P.K., Gangopadhyay, A., Mani, P.K., Kundu,
652 A.L., Mazumdar, D., 2008. Organic Amendments Influence Soil Organic Carbon Pools
653 and Rice–Wheat Productivity. *Soil Sci. Soc. Am. J.* 72, 775-785.

654 Manlay, R.J., Feller, C., Swift, M.J., 2007. Historical evolution of soil organic matter concepts
655 and their relationships with the fertility and sustainability of cropping systems. *Agr.*
656 *Ecosyst. Environ.* 119, 217-233.

657 Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of
658 phosphate in natural waters. *Anal. Chim. Acta.* 27, 31-36.

659 Oelofse, M., Markussen, B., Knudsen, L., Schelde, K., Olesen, J.E., Jensen, L.S., Bruun, S.,
660 2015. Do soil organic carbon levels affect potential yields and nitrogen use efficiency?
661 An analysis of winter wheat and spring barley field trials. *Eur. J. Agron.* 66, 62-73.

662 Olsen, R.J., Hensler, R.F., Attoe, O.J., 1970. Effect of manure application, aeration, and soil
663 pH on soil nitrogen transformations and on certain soil test values1. *Soil Sci. Soc. Am. J.*
664 34, 222-225.

665 Olsen, S.R., Cole, C.V., Watanabe, F.S. 1954. Estimation of available phosphorus in soils by
666 extraction with sodium bicarbonate, Washington, USDA.

667 Page, A.L., Miller, R.H., (ed.), D.R.K., 1982. Methods of soil analysis. Part 2. Chemical and
668 Microbiological Properties. Second Edition. *Agron. Monogr.* 9. ASA and SSSA, Madison,
669 WI.

670 Pan, G.X., Smith, P., Pan, W.N., 2009. The role of soil organic matter in maintaining the
671 productivity and yield stability of cereals in China. *Agr. Ecosyst. Environ.* 129, 344-348.

672 Pan, G.X., Zhou, P., Zhang, X.H., Qiu, D.S., Chu, Q.H., 2006. Effect of different fertilization

- practices on crop carbon assimilation and soil carbon sequestration: a case study of a paddy under a long term fertilization trial from the Tai Lake region, China. *Acta Ecol. Sin.* 26, 3704-3710 (in Chinese with English summary).
- Patrick, M., Tenywa, J.S., Ebanyat, P., Tenywa, M.M., Mubiru, D.N., Basamba, T.A., Leip, A., 2013. Soil organic carbon thresholds and nitrogen management in tropical agroecosystems: concepts and prospects. *J. Sust. Dev.* 6, 31-43.
- Qin, Z.C., Huang, Y., Zhuang, Q.L., 2013. Soil organic carbon sequestration potential of cropland in China. *Global Biogeochem. Cy.* 27, 711-722.
- Rasmussen, P.E., Collins, H.P., 1991. Long-Term Impacts Of Tillage, Fertilizer, And Crop Residue On Soil Organic Matter In Temperate Semiarid Regions. In: Nyle, C.B. (Ed.), *Adv. Agron. Academic Press*, pp. 93-134.
- Rasmussen, P.E., Parton, W.J., 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. *Soil Sci. Soc. Am. J.* 58, 523-530.
- Seremesic, S., Milosev, D., Djalovic, I., Zeremski, T., Ninkov, J., 2011. Management of soil organic carbon in maintaining soil productivity and yield stability of winter wheat. *Plant Soil Environ.* 57, 216-221.
- Shi, R., 1976. Soil and agricultural chemistry analysis. (In Chinese.) China Agriculture Press, Beijing.
- Six, J., Feller, C., Denef, K., Ogle, S.M., de Moraes, J.C., Albrecht, A. 2002. Soil organic matter, biota and aggregation in temperate and tropical soils - Effects of no-tillage. *Agronomie.* 22: 755-775.
- Smith, P., 2004. Carbon sequestration in croplands: the potential in Europe and the global context. *Eur. J. Agron.* 20, 229-236.
- SPSS Inc. (1999). SPSS base 17.0 for Windows user's guide. SPSS Inc., Chicago IL.
- Srinivasarao, C., Venkateswarlu, B., Lal, R., Singh, A.K., Vittal, K.P.R., Kundu, S., Singh, S.R., Singh, S.P., 2012. Long-Term Effects of Soil Fertility Management on Carbon Sequestration in a Rice–Lentil Cropping System of the Indo-Gangetic Plains. *Soil Sci. Soc. Am. J.* 76, 168-178.
- SSSC (2000) Soil Science Society of China. Methods of soil agrochemistry analysis. Chinese Agriculture Science and Technology Press, Beijing, China (in Chinese)
- Sun, W., Huang, Y., Zhang, W., Yu, Y., 2010. Carbon sequestration and its potential in agricultural soils of China. *Global Biogeochem. Cy.* 24, GB3001.
- Tian, K., Zhao, Y., Xu, X., Hai, N., Huang, B., Deng, W., 2015. Effects of long-term fertilization and residue management on soil organic carbon changes in paddy soils of China: A meta-analysis. *Agriculture, Ecosystems & Environment* 204, 40-50.
- Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic matter in sustaining soil fertility. *Nature* 371, 783-785.
- Walkley, A., Black, I.A., 1934. An examination of the degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 37, 29-38.
- Wen, G., Winter, J.P., Voroney, R.P., Bates, T.E., 1997. Potassium availability with application of sewage sludge, and sludge and manure composts in field experiments. *Nutr. Cycl. Agroecosys.* 47, 233-241.
- Yan, X.Y., Gong, W., 2010. The role of chemical and organic fertilizers on yield, yield

- variability and carbon sequestration- results of a 19-year experiment. *Plant Soil* 331, 471-480.
- Yang, J., Gao, W., Ren, S., 2015. Long-term effects of combined application of chemical nitrogen with organic materials on crop yields, soil organic carbon and total nitrogen in fluvo-aquic soil. *Soil and Tillage Research* 151, 67-74.
- Yu, G.R., Fang, H.J., Gao, L.P., Zhang, W.J., 2006. Soil organic carbon budget and fertility variation of black soils in Northeast China. *Ecol. Res.* 21, 855-867.
- Zhang, W.J., Wang, X.J., Xu, M.G., Huang, S.M., Liu, H., Peng, C., 2010. Soil organic carbon dynamics under long-term fertilizations in arable land of northern China. *Biogeosciences* 7, 409-425.
- Zhang, W., Xu, M., Wang, B., Wang, X., 2009. Soil organic carbon, total nitrogen and grain yields under long-term fertilizations in the upland red soil of southern China. *Nutr Cycl Agroecosys* 84(1), 59-69.
- Zhang, X.B., Xu, M.G., Sun, N., Wang, X.J., Wu, L., Wang, B.R., Li, D.C., 2013. How do environmental factors and different fertilizer strategies affect soil CO₂ emission and carbon sequestration in the upland soils of southern China? *Appl. Soil Ecol.* 72, 109-118.
- Zhu, L., Li, J., Tao, B., Hu, N., 2015. Effect of different fertilization modes on soil organic carbon sequestration in paddy fields in South China: A meta-analysis. *Ecological Indicators* 53, 144-153.

Figure legends

Fig.1 Geographic locations of the long-term experimental sites. North East: Haerbin (HEB), Gongzhuling (GZL-A and -B), and Shenyang (SY); North West: Urumqi (UM), Zhangye (ZY), Pingliang (PL) and Yangling (YL); North: Changping (CP), Tianjin (TJ), Yucheng (YC), Zhengzhou (ZZ) and Xuzhou (XZ); South region: Suining (SN), Chongqing (CQ), Qiyang (QY) and Jinxian (JX).

Fig.2 Average yield variation (%) for wheat and maize for different treatments over the experimental period in each region. In a given region, treatments with a different letter (upper case for wheat or lowercase for maize) are significantly different at $P < 0.01$ as shown by LSD following one-way ANOVA. The error bar in each treatment is the standard deviation. CK is the unfertilized Control. N/A means that there was no NPS treatment in the North east, North and South region.

Fig.3 Annual C inputs from crop residues and manure/straw in different regions. In a given region, treatments with different lower case letter have a significantly different C input by crop biomass at $P < 0.01$ as shown by LSD following one-way ANOVA. Different uppercase letters show significant difference ($P < 0.01$) in total C input between the treatments. The error bar in each treatment is the standard deviation. Data for the NPS treatment sufficient for analysis were available only in the North West region.

Fig.4 Relationships between total cumulative C inputs and the increase in SOC stocks over the experimental period in different regions. n is the number of data points with data pooled from different fertilizer treatments and sites. Linear regression with groups indicated that slopes differed significantly between regions at $P < 0.01$.

Fig.5 Relationship between SOC stocks in the top 20 cm and relative yields of wheat (a) and maize (b) in different regions. n is the number of data points with data pooled from different fertilizer treatments, years and sites. The different symbols indicate the

different fertilizer treatments; relative yield of the NPK reference treatment was 1.0 (symbols not shown).

Fig.6 Relationship between SOC stocks in the 20 cm soil depth and yield variation of wheat and maize. Each value is the yield variation for a given fertilizer treatment at a site calculated over the experimental period and plotted against the average SOC stocks for the treatment over the same period.

Table 1. Cropping rotation and annual inorganic nitrogen (N), phosphorus (P) and potassium (K) fertilizer application rate (kg ha⁻¹) for different treatments at the 17 long-term experimental sites in China.

Region	Site	Cropping system	Experiment duration	Crop	N application rate (kg N ha ⁻¹)				P application rate (kg P ha ⁻¹)	K application rate (kg K ha ⁻¹)
					NP/NPK	NPM/NPKM	hNPKM	NPS/NPKS		
North East	HEB	DC [¶]	1980-2006	Maize/Wheat	150	150	N/A	N/A	75/75	75/75
	GZL-A	MC [‡]	1990-2009	Maize	165	50	74	112	82.5	82.5
	GZL-B	MC	1980-2010	Maize	150	150	150	N/A	75	75
	SY	MC	1979-2012	Maize	120	120	180	N/A	60	60
North	CP	DC	1990-2008	Maize/Wheat	150	150	150	150	75/75	45/45
	TJ	DC	1979-2010	Maize	210	105	N/A	210	0	0
				Wheat	285	142.5	N/A	285	95	47.5
	YC	DC	1986-2010	Maize/Wheat	187.5	187.5	187.5	N/A	150/150	75/75
	ZZ	DC	1990-2010	Maize	188	50	282	188	93.8	93.8
				Wheat	165	50	74	165	82.5	82.5
	XZ	DC	1981-2012	Maize	150	150	N/A	N/A	75	112.5
				Wheat	150	150	N/A	N/A	75	112.5
North West	UM	MC	1990-1994	Maize/wheat	99	30	99	99	145.5/145.5	42/42

			1995-2012	Maize/wheat	242	85	152	217	300/300	112.5/112.5
	ZY	MC	1982-1990	Maize	240	240	N/A	N/A	120	120
				Wheat	120	120	N/A	N/A	60	60
			1991-2012	Maize	300	300	N/A	N/A	180	90
				Wheat	150	150	N/A	N/A	90	45
	PL	MC	1979-2012	Maize/wheat	90	90	N/A	90	30/30	0
	YL	DC	1990-2010	Maize	188	56	188	188	94	94
				Wheat	165	50	248	165	82.5	82.5
South	SN	DC	1981-2011	Wheat/rice	120	120	N/A	N/A	60/60	60/60
	CQ	DC	1991-2012	Wheat/rice	150	150	225	150	75/75	75/75
	QY	DC	1990-2012	Maize	210	63	95	210	84	84
				Wheat	90	27	41	90	36	36
	JX	DC	1981-2007	Maize/maize	60	60	N/A	N/A	30/30	60/60

[¶] double-cropping

[‡] mono-cropping

N/A: no data available.

Table 2. Mean annual change in crop yields (kg ha⁻¹ yr⁻¹) over time for the 17 long-term experimental sites in China (n= 20-30).

Region	Sites	Crop	Control	NP	NPK	NPM	NPKM	hNPKM	NPS	NPKS
North	HEB	Wheat	-30.8	33.4	107.5*	74.3	107.9*	78.1*	N/A	N/A
East		Maize	-63.0	185.5*	169.5*	162.6*	175.4*	44.6*	N/A	N/A
	GZL-A	Maize	-14.9	26.5	71.9	N/A	146.8**	107.4*	N/A	121.4**
	GZL-B	Maize	-37.5**	54.3*	87.3**	103.3**	109.4**	72.0*	N/A	N/A
	SY	Maize	23.7*	N/A	27.7**	N/A	38.4**	42.9**	N/A	N/A
North	CP	Wheat	-48.1**	-94.8*	106.6*	N/A	120.1*	124.2*	N/A	72.0*
		Maize	-101.6**	-30.3	75.6	N/A	92.2*	191.7**	N/A	91.1*
	TJ	Wheat	-41.1**	-49.7*	-38.5*	N/A	-60.4**	-36.7*	N/A	-133.8**
		Maize	34.4	-8.3	30.1	N/A	45.7	20.7	N/A	40.3
	YC	Wheat	-21.5	N/A	-59.8	N/A	113.1	N/A	N/A	N/A
		Maize	-218.7*	N/A	-146.6*	N/A	-103.2	N/A	N/A	N/A
	ZZ	Wheat	-26.3*	58.9*	80.3*	N/A	74.8*	53.1*	N/A	36.6
		Maize	-90.7**	121.0*	150.0*	N/A	133.7*	131.9*	N/A	107.8*
	XZ	Wheat	-51.2**	-102.4**	-81.4**	-46.5**	-35.4*	N/A	N/A	N/A
		Maize	-71.4**	-70.3**	-82.2**	-49.9**	-62.4*	N/A	N/A	N/A
North	UM	Wheat	-6.9	103.5*	125.1*	N/A	124.5*	153.5*	N/A	131.3*
West		Maize	-63.5	86.5	194.1*	N/A	116.4	188.5*	N/A	204.4*
	ZY	Wheat	-132.1**	-14.5	21.6	33.2*	66.2*	N/A	N/A	N/A

South	PL	Maize	-321.4**	-53.7	41.1	125.8*	121.4*	N/A	N/A	N/A
		Wheat	-32.1*	-53.5	N/A	-80.6	N/A	N/A	-60.4	N/A
		Maize	53.8	152.5*	N/A	187.3**	N/A	N/A	195.4**	N/A
	YL	Wheat	4.9	102.2*	125.3**	N/A	173.5**	153.8**	N/A	147.8**
		Maize	18.6	5.9	17.3	N/A	31.9	47.7	N/A	5.7
	SN	Wheat	2.9	-25.4	17.7	-35.8	25.2	N/A	N/A	N/A
	CQ	Wheat	-23.7*	-12.5	35.2	N/A	16.59	61.0	N/A	-10.0
	QY	Wheat	-10.4*	-99.1**	-86.7**	N/A	2.4	12.2	N/A	-85.4**
		Maize	-21.7**	-193.5**	-181.4**	N/A	105.0*	17.4	N/A	-197.9**
	JX	Maize	-7.7	-13.3	-16.4	N/A	-9.5	N/A	N/A	N/A
		Maize	11.4	-10.4	25.5	N/A	25.8	N/A	N/A	N/A

Values with * (P<0.05) or ** (P<0.01) indicate a significant linear regression between crop yields and the number of years since the experiment started. N/A: no data available.

Table 3. Relative yield from different treatments relative to the NPK reference treatment averaged over the experimental period in the different regions (n=4 or 5).

Crop	Treatment	Average relative yields			
		North East	North West	North	South
Wheat	Control	0.63(0.06) b	0.35(0.02) d	0.29(0.01) c	0.52(0.14) e
	NP	0.94(0.05) a	0.94(0.02) c	0.88(0.02) b	0.78(0.06) d
	NPK	1.00 a	1.00 b	1.00 a	1.00 c
	NPM	1.03(0.02) a	1.09(0.02) a	1.04(0.01) a	2.46(0.49) a
	NPKM	1.05(0.02) a	1.11(0.02) a	1.05(0.01) a	2.53(0.52) a
	hNPKM	1.06(0.03) a	1.12(0.03) a	1.07(0.02) a	2.61(0.54) a
	NPS	N/A	1.04(0.02) b	N/A	N/A
	NPKS	1.01(0.04) a	1.07(0.04) a	0.99(0.04) b	1.22(0.06) b
Maize	Control	0.50(0.02) D	0.39(0.03) C	0.43(0.01) C	0.12(0.02) C
	NP	0.94(0.01) C	1.02(0.03) B	0.91(0.02) B	0.59(0.07) C
	NPK	1.00 B	1.00 B	1.00 A	1.00 B
	NPM	1.05(0.01) A	1.10(0.02) A	1.04(0.01) A	2.51(0.26) A
	NPKM	1.06(0.01) A	1.13(0.03) A	1.04(0.01) A	2.52(0.23) A
	hNPKM	1.09(0.02) A	1.15(0.03) A	1.08(0.01) A	2.54(0.22) A
	NPS	N/A	1.02(0.03) B	N/A	N/A
	NPKS	1.01(0.02) B	1.04(0.02) B	1.08(0.03) A	1.27(0.05) B

Numbers in parentheses are standard deviation and within a column treatments followed by a different lowercase letter (wheat) and uppercase letter (maize) are significantly different between treatments at $P < 0.05$ as shown by LSD following one-way ANOVA. N/A: no data available.

Table 4. SOC storage in the top 20 cm soil depth under different treatments in different regions at beginning and end of experimental period (n=4 or 5).

Treatment	Period	Average SOC storage (Mg C ha ⁻¹)			
		North East	North West	North	South
Control	beginning	31.9(1.0) c	19.8(0.5) d	19.3(0.8) d	20.6(0.5) c
	end	29.1(1.3) c	17.9(0.3) e	17.2(1.2) e	18.1(0.6) c
NP	beginning	31.9(1.0) c	19.8(0.5) d	19.3(0.8) d	20.6(0.5) d
	end	32.8(0.9) c	22.4(0.3) c	22.6(0.7) c	22.1(0.5) c
NPK	beginning	31.9(1.0) c	19.8(0.5) d	19.3(0.8) d	20.6(0.5) c
	end	33.6(0.9) c	23.5 (0.3) c	23.8(0.6) c	24.8(0.5) b
NPM	beginning	31.9(1.0) c	19.8(0.5) d	19.3(0.8) d	20.6(0.5) c
	end	42.9(0.9) a	37.5(0.6) a	32.1(0.5) a	33.6(1.3) a
NPKM	beginning	31.9(1.0) c	19.8(0.5) d	19.3(0.8) d	20.6(0.5) c
	end	44.5(1.0) a	38.1(0.6) a	33.8(0.5) a	34.2(1.1) a
hNPKM	beginning	31.9(1.0) c	19.8(0.5) d	19.3(0.8) d	20.6(0.5) c
	end	45.1(1.2) a	39.8(0.7) a	34.2(0.6) a	34.7(1.4) a
NPS	beginning	N/A	19.8(0.5) d	N/A	N/A
	end	N/A	27.2(0.5) b	N/A	N/A
NPKS	beginning	31.9(1.0) c	19.8(0.5) d	19.3(0.8) d	20.6(0.5) c
	end	35.2(1.0) b	27.5(0.6) b	28.6(1.4) b	25.1(0.9) b

Numbers in parentheses are standard deviation and within a column treatments followed by a different lowercase letter (wheat) and uppercase letter (maize) are significantly different at $P < 0.05$ as shown by LSD following one-way ANOVA.

Table 5. Mean rate of change ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$) of the SOC stocks over time at the 17 long-term experimental sites in China (n= 20-30).

Region	Sites	Control	NP	NPK	NPM	NPKM	hNPKM	NPS	NPKS
North East	HEB	-0.13*	-0.10	-0.04	-0.03	-0.08	0.11	N/A	N/A
	GZL-A	-0.09	0.09	0.21	N/A	0.90**	0.83**	N/A	0.18*
	GZL-B	-0.08	-0.14	-0.04	0.32**	0.41**	0.68**	N/A	N/A
	SY	-0.18**	N/A	-0.015	N/A	0.23**	0.30**	N/A	N/A
North	CP	0.29*	0.36**	0.22	N/A	0.48**	0.72**	N/A	0.42**
	TJ	0.15	0.27**	0.26**	N/A	0.61**	0.94**	N/A	0.25**
	YC	0.29**	N/A	0.41**	N/A	1.08**	N/A	N/A	N/A
	ZZ	-0.12*	0.15*	0.12*	N/A	0.42**	0.70**	N/A	0.25*
	XZ	0.002	0.12**	0.08**	0.39**	0.35**	N/A	N/A	N/A
North West	UM	-0.18**	-0.04	-0.15*	N/A	0.75**	1.38**	N/A	0.02
	ZY	-0.29*	-0.08	-0.16	0.24**	0.18*	N/A	N/A	N/A
	PL	0.04	0.14*	N/A	0.50**	N/A	N/A	0.34**	N/A
	YL	0.18**	0.42**	0.46**	N/A	1.09**	1.29**	N/A	0.62**
South	SN	0.01	-0.06	0.02	0.01	0.00	N/A	N/A	N/A
	CQ	-0.23	0.09	0.05	N/A	0.43*	0.65**	N/A	0.37*
	QY	-0.06	0.12	0.17	N/A	0.70**	0.78**	N/A	0.22**
	JX	-0.08	-0.05	-0.08	N/A	0.20	N/A	N/A	N/A

Values with * ($P < 0.05$) or ** ($P < 0.01$) indicate a significant linear relationship between SOC storage and the number of years since the experiment started. N/A: no data available.

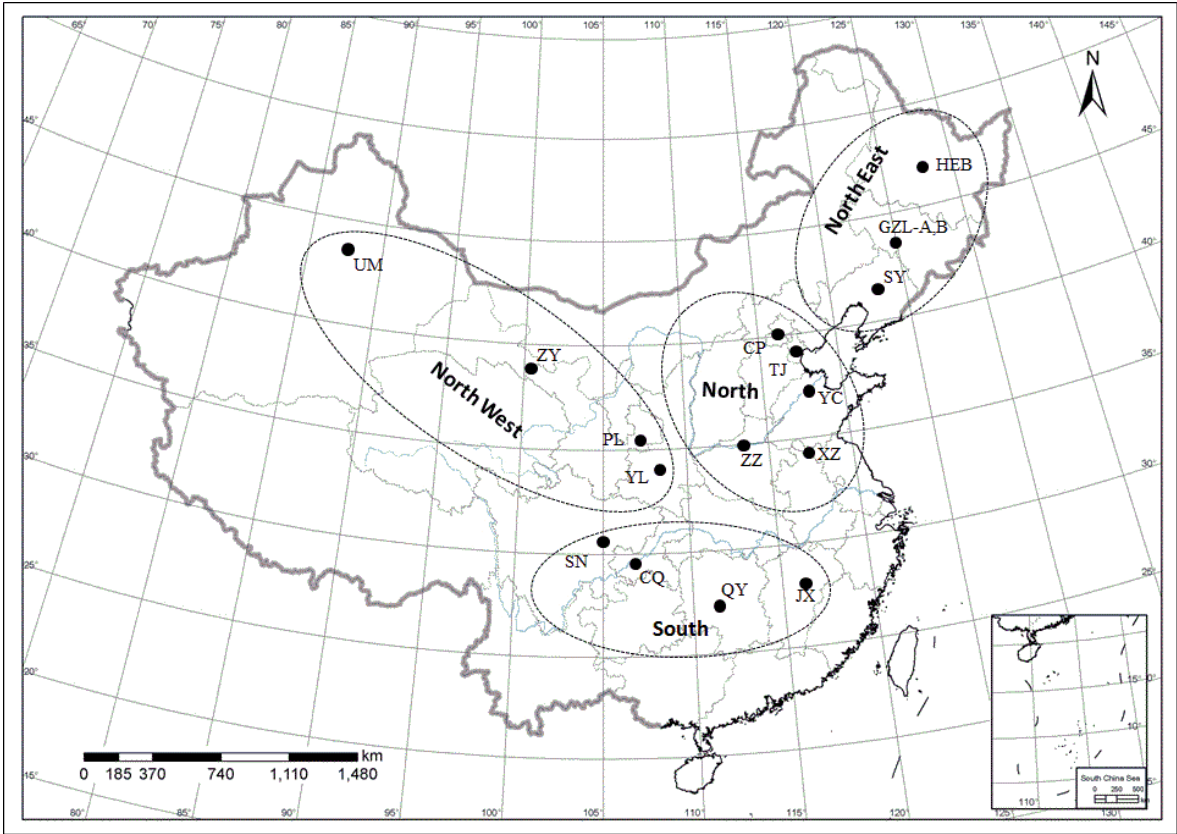


Fig.1

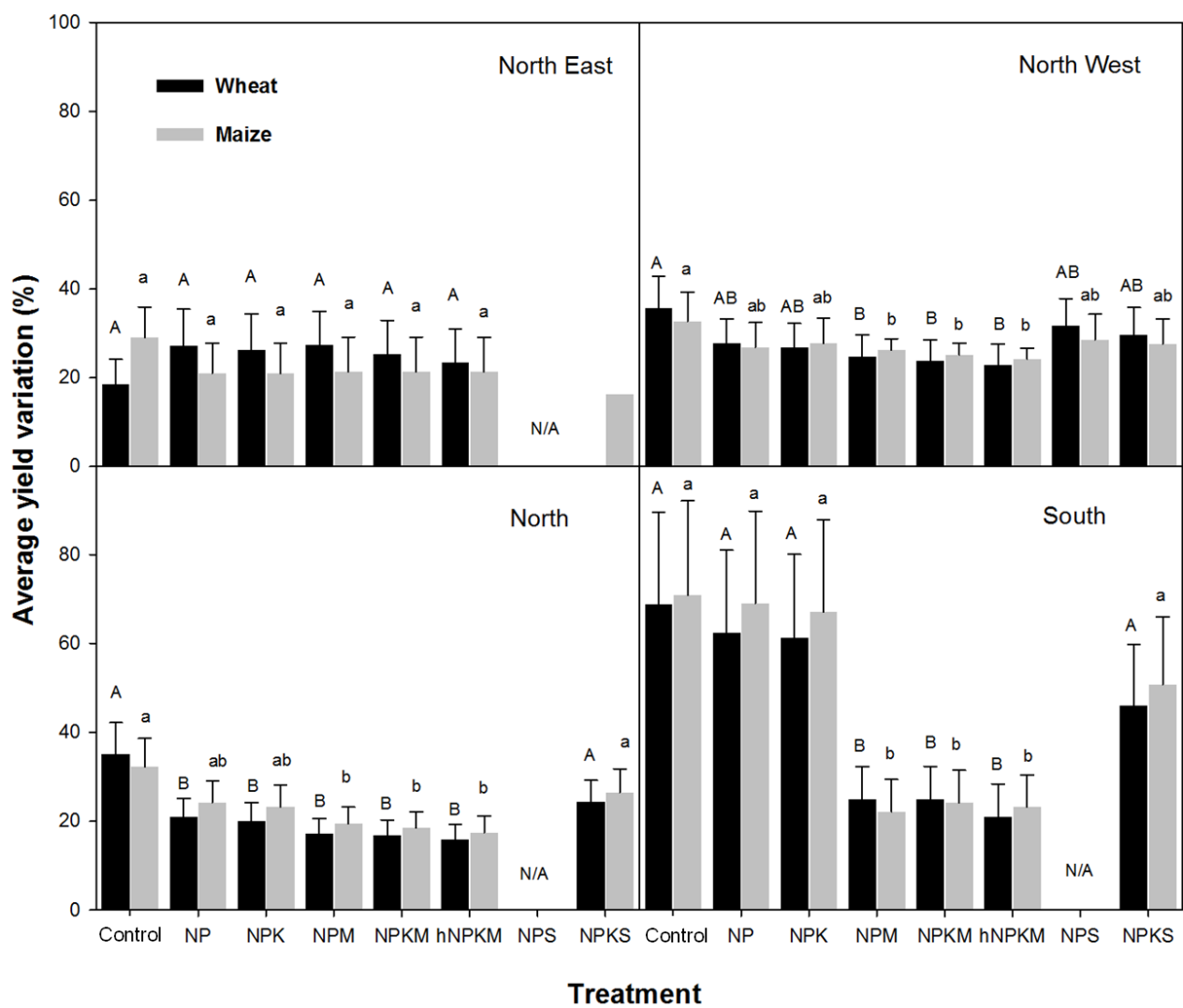


Fig.2

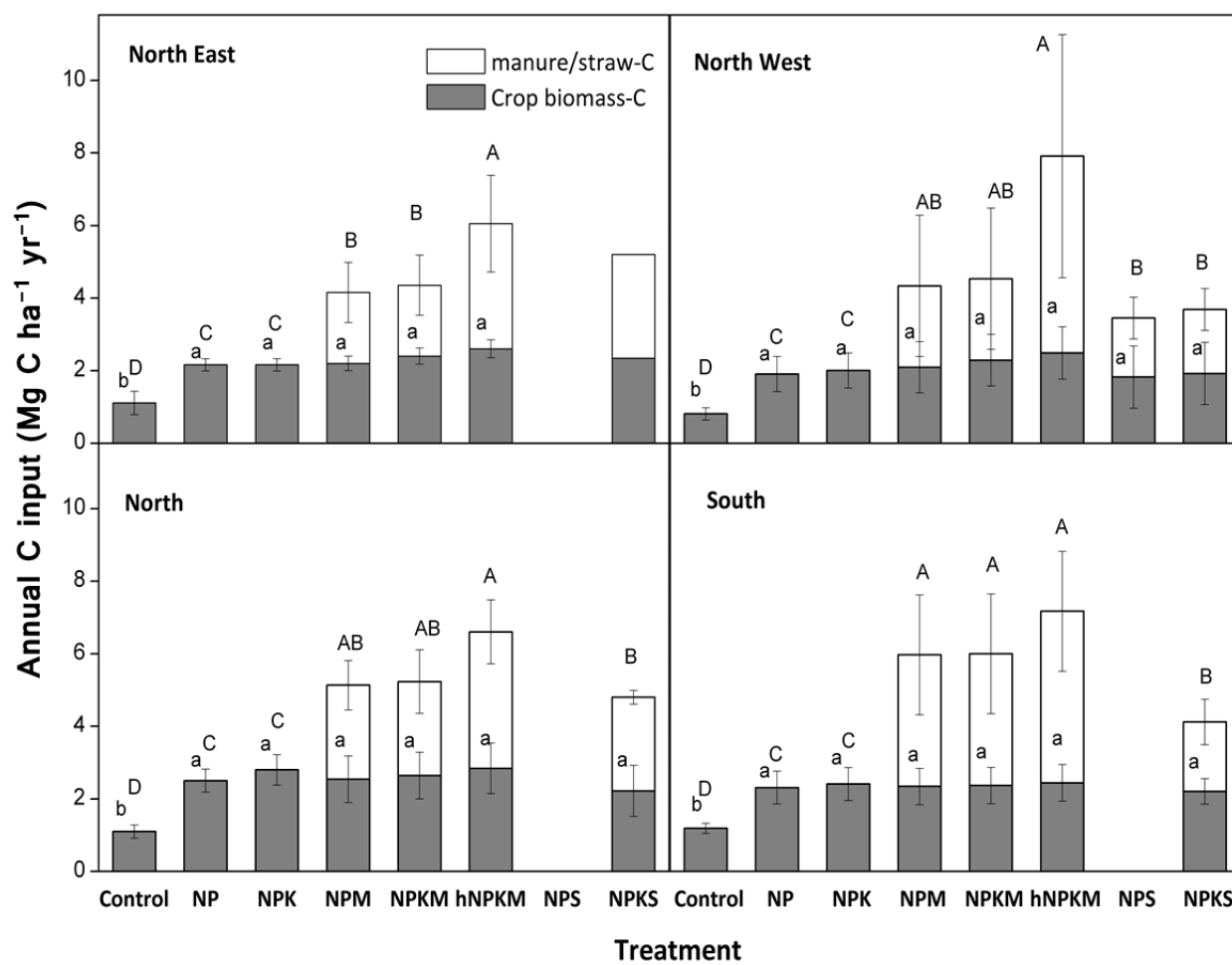


Fig.3

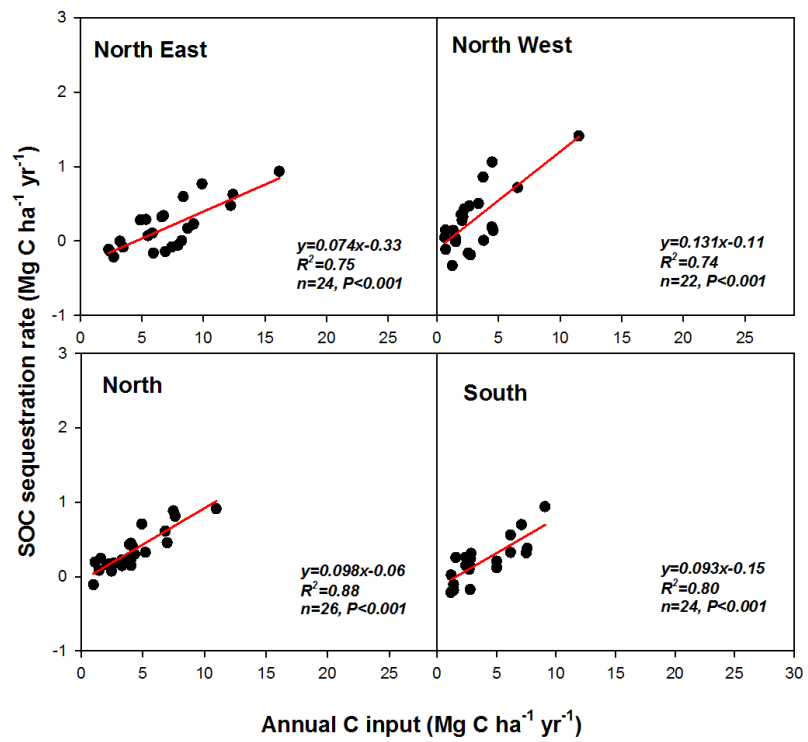


Fig.4

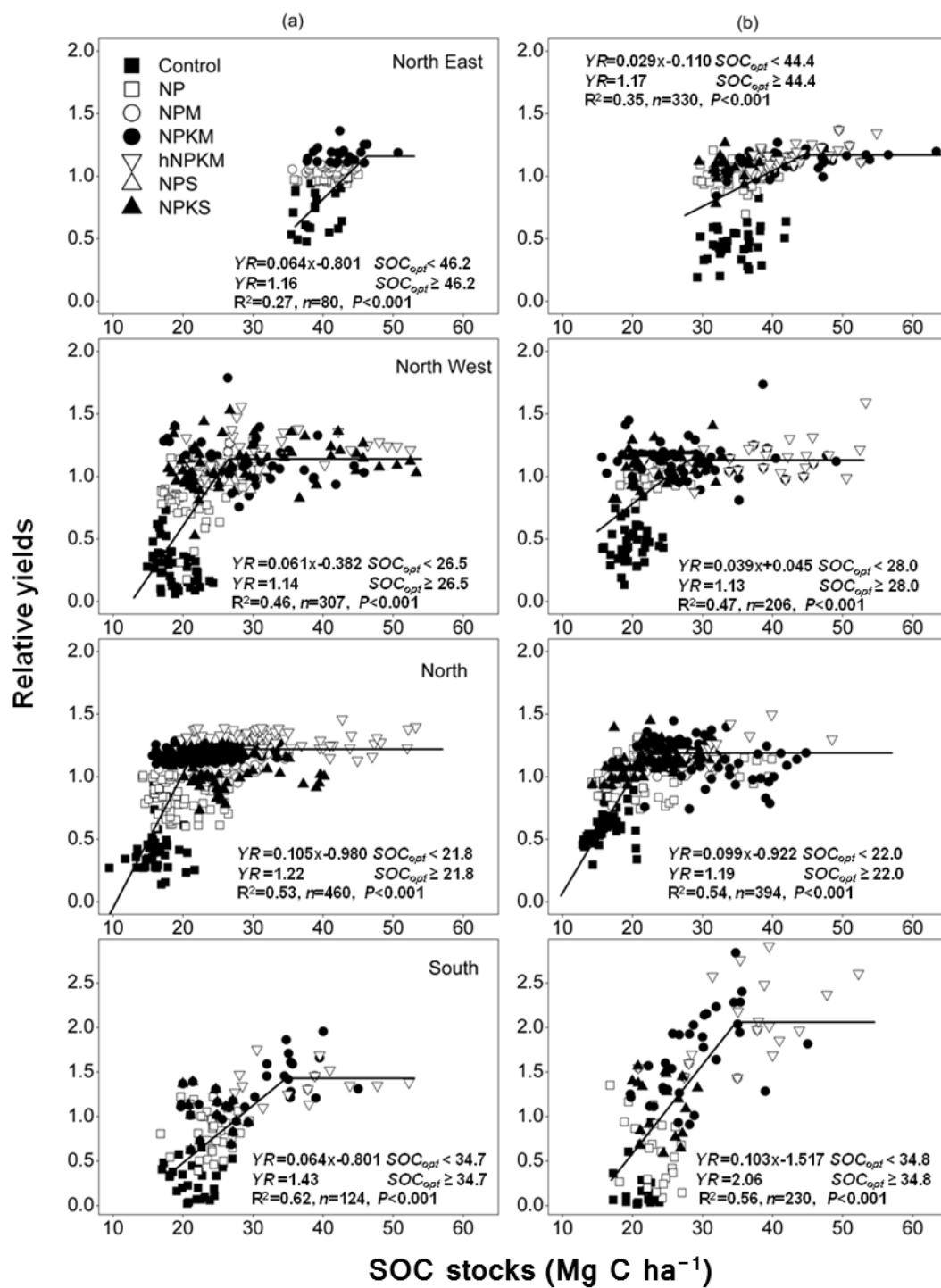


Fig.5

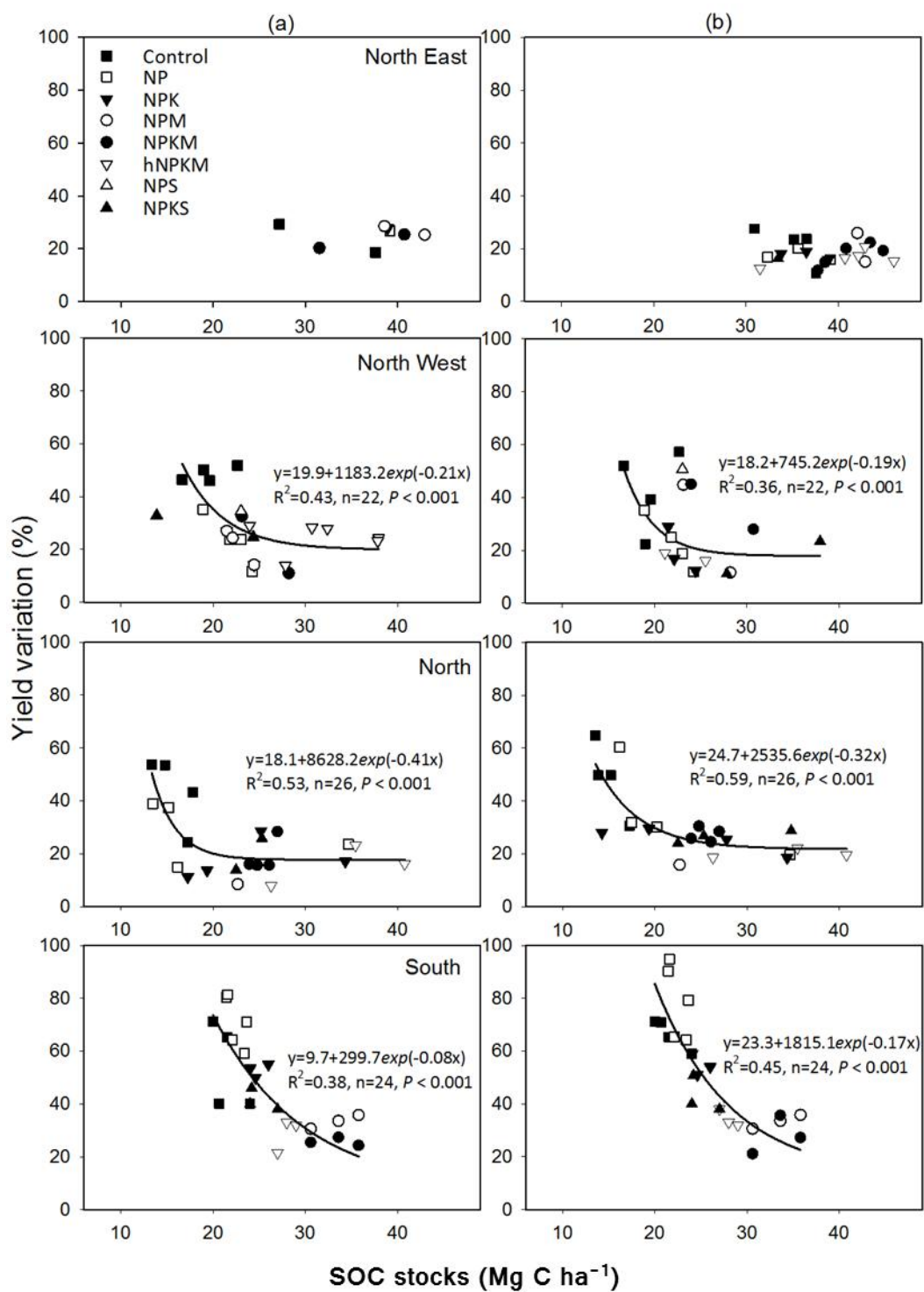


Fig.6

Auxiliary material for

Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: evidence from long-term experiments with wheat-maize cropping systems in China

Xubo Zhang ^{1, 2}, Nan Sun ^{1*}, Lianhai Wu ², Minggang Xu ^{1*}, Ian J Bingham ³, Wenju Zhang ¹, Zhongfang Li ⁴

¹ Ministry of Agriculture Key Laboratory of Crop Nutrition and Fertilization, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China.

² Sustainable Soils and Grassland Systems Department, Rothamsted Research, North Wyke, Okehampton, Devon EX20 2SB, UK.

³ Crop & Soil Systems Research, SRUC, Kings Buildings, West Mains Rd, Edinburgh EH9 3JG, UK

⁴ Chemistry and Bioengineering College, Hezhou University, Hezhou 542899, China.

* Corresponding author:

xuminggang@caas.cn; sunnan@caas.cn

Tel.: +86 10 82105636; FAX: +86 10 82106225;

Table S1. Geographic information, climatic conditions, annual irrigation and tillage for the 17 long-term fertilization experiments in China

Region	Sites	Start year	End year for study	Longitude	Latitude	Climate type ¶	T ‡ (°C)	Rainfall (mm)	AE * (mm)	Annual irrigation (times, mm§)	Tillage (times, depth)
North East	Haerbin (HEB)	1980	2006	126°35'15"	45°40'20"	MT-SH	3.5	533	1509	0, 0	1, 0- 20cm
	Gongzhuling-A (GZL-A)	1990	2009	124°48'33"	43°30'23"	MT-SH	4.5	525	1400	0, 0	2, 0- 20cm
	Gongzhuling-B (GZL-B)	1979	2010	124°48'50"	43°30'10"	MT-SH	4.5	525	1400	0, 0	2, 0- 20cm
	Shenyang (SY)	1979	2012	123°33'15"	40°48'20"	MT-SH	7.7	547	1330	0, 0	1, 0- 20cm
North	Changping (CP)	1991	2008	116°15'23"	40°13'22"	WT-SH	11.0	600	2301	0, 0	2, 0- 20cm
	Tianjin (TJ)	1979	2010	117°06'10"	39°10'50"	WT-SH	11.6	607	1736	2, 50-100	2, 0- 20cm
	Yucheng (YC)	1986	2010	115°45'05"	36°24'10"	WT-SH	13.4	560	2095	2, 50-100	2, 0- 20cm
	Zhengzhou (ZZ)	1990	2010	111°52'21"	26°45'13"	WT-SH	14.3	632	1450	2-3, 80-200	2, 0- 20cm
	Xuzhou (XZ)	1980	2012	117°17'30"	34°17'00"	WT-SH	14.5	832	2200	0, 0	2, 0- 20cm
North West	Urumqi (UM)	1990	2012	87°46'50"	43°57'10"	MT-SA	7.7	310	2570	6-8, 450-480	1, 0- 20cm
	Zhangye (ZY)	1990	2012	100°18'50"	38°36'20"	MT-A	7.0	127	2345	5-6, 330-485	1, 0- 20cm
	Pingliang (PL)	1978	2012	107°30'15"	35°16'15"	MT-A	8.0	540	1384	0, 0	1, 0- 20cm
	Yangling (YL)	1990	2012	108°00'48"	34°17'51"	WT-SH	13.8	525	993	1, 60-90	2, 0- 20cm
South	Suining (SN)	1981	2011	106°10'58"	30°10'52"	ST-HM	17.4	930	1100	0, 0	2, 0- 20cm
	Chongqing (CQ)	1991	2012	103°26'05"	30°26'10"	ST-HM	18.3	1136	990	0, 0	2, 0- 20cm
	Qiyang (QY)	1990	2012	111°52'32"	26°45'12"	ST-H	18.0	1255	1470	0, 0	2, 0- 20cm
	Jinxian (JX)	1981	2007	116°20'15"	28°15'15"	ST-HM	17.5	1581	1606	0, 0	2-3, 0- 20cm

¶ MT, mid-latitude temperate; WT, warm-temperate; ST, sub-tropical; SH, semi-humid; SA, semi-arid; A, arid; HM, humid monsoon; H, humid.

‡ mean annual temperature; * annual evaporation; § total annual irrigation

Note: Climate data were collected from the China meteorological sharing service system (<http://cdc.cma.gov.cn/>)

Table S2. Soil properties (0-20 cm) at the beginning of the long-term fertilization experiments in China

Region	Sites	Soil classification (FAO WRB)	SOC ^s (g·kg ⁻¹)	Total			Available			pH (1:1, water/soil)	Soil Bulk density (g cm ⁻³)	Clay (<2μm, %)
				N [*] (g kg ⁻¹)	P [†] (g kg ⁻¹)	K [‡] (g kg ⁻¹)	N [†] (mg kg ⁻¹)	P [‡] (mg kg ⁻¹)	K [¶] (mg kg ⁻¹)			
North East	HEB	Luvic Phaeozems	15.5	1.47	1.07	25.16	151.1	51.0	200.0	7.2	1.28	12.9
	GZL-A	Luvic Phaeozems	13.5	1.40	1.39	22.1	114.0	27.1	190.1	7.6	1.19	31.1
	GZL-B	Luvic Phaeozems	16.1	1.90	1.39	22.1	114.5	27.0	190.0	6.7	1.16	31.0
	SY	Gleyic Luvisols	9.2	1.33	0.80	20.1	105.5	6.5	97.9	6.5	1.18	N/A
North	CP	Haplic Luvisol	7.1	0.64	0.69	14.6	49.7	4.6	65.3	8.2	1.58	10.2
	TJ	Calcaric Cambisol	10.9	1.00	1.60	N/A	75.1	15.8	203.8	5.7	1.28	N/A
	YC	Calcaric Cambisol	3.93	0.50	N/A	N/A	37.5	17.2	88.0	N/A	1.21	21.4
	ZZ	Calcaric Cambisol	6.7	1.01	0.65	16.9	76.6	6.5	74.0	8.3	1.49	13.4
	XZ	Calcaric Cambisol	6.5	0.66	0.74	22.7	68	12.0	62.0	8.0	1.25	5.9
North West	UM	Haplic Calcisol	8.8	0.87	0.67	19.8	55.2	3.4	288.0	8.1	1.25	21.0
	ZY	Orthic Anthrosol	11.5	0.76	0.82	16.8	28.1	21.7	99.1	8.5	1.20	19.5
	PL	Cumul Haplic Kastanozem	5.2	0.95	0.62	20.5	114.0	4.8	163.2	8.2	1.30	33.6
	YL	Calcaric Regosol	6.3	0.83	0.61	22.8	61.3	9.6	191.0	8.6	1.27	16.8
South	SN	Regosols	9.2	1.09	1.35	26.9	66.3	3.9	130.6	8.6	1.27	N/A
	CQ	Regosols	13.9	1.25	0.67	21.1	93.0	4.3	562.0	7.7	1.37	27.5
	QY	Eutric Cambisol	6.0	1.07	0.45	13.7	79.0	10.8	122.0	5.7	1.19	40.9
	JX	Eutric Cambisol	9.4	0.98	0.62	11.4	60.3	5.63	84.3	6.0	1.20	32.2

^sSoil organic carbon^{*}Nitrogen[†]Phosphorus[‡]Potassium[†]Alkaline hydrolysable N[‡]Olsen P[¶]NH₄OAc-extractable K

N/A means no data available.

Table S3. Treatments at the 17 long-term experimental sites in China (+: included; None: no treatment)

Region	Sites	Plot size (m ²)	Replicates	Control	NP/NPK	NPS/NPKS	NPM/NPKM	hNPKM
North East	HEB	168	1	+	+	None	+	+
	GZL-A	400	1	+	+	+	+	+
	GZL-B	100	1	+	+	None	+	+
North	SY	160	3	+	+	None	+	+
	CP	100	1	+	+	+	+	+
	TJ	17	4	+	+	+	+	+
	YC	28	4	+	+	None	+	None
	ZZ	400	1	+	+	+	+	+
	XZ	33.3	4	+	+	None	+	None
	UM	468	1	+	+	+	+	+
North West	ZY	33.3	3	+	+	None	+	None
	PL	220	3	+	+	+	+	None
	YL	196	1	+	+	+	+	+
	SN	13.2	4	+	+	None	+	None
South	CQ	120	1	+	+	+	+	+
	QY	196	2	+	+	+	+	+
	JX	22.2	3	+	+	None	+	None

